

1 **New Insights about Cloud Vertical Structure from CloudSat and**
2 **CALIPSO observations**

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4 By
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16 Key points:

- 17 (1) Complex cloud vertical structure (CVS) can be reduced to a few major classes
18 (2) These CVS classes vary substantially in space and time and have very distinct radiative
19 effects
20 (3) Previous interpretations of cloud regimes from passive observations are largely
21 consistent with the blend of CVS classes they consist of

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31

Abstract

32 Active cloud observations from A-Train's CloudSat and CALIPSO satellites offer new
33 opportunities to examine the vertical structure of hydrometeor layers. We use the 2B-
34 CLDCLASS-LIDAR merged CloudSat-CALIPSO product to examine global aspects of hydrometeor
35 vertical stratification. We group the data into major Cloud Vertical Structure (CVS) classes based
36 on our interpretation of how clouds in three standard atmospheric layers overlap, and provide
37 their global frequency of occurrence. The two most frequent CVS classes are single-layer (per
38 our definition) low and high clouds which represent ~53% of cloudy skies, followed by high
39 clouds overlying low clouds, and vertically extensive clouds that occupy near-contiguously a
40 large portion of the troposphere. The prevalence of these configurations changes seasonally
41 and geographically, between daytime and nighttime, and between continents and oceans. The
42 radiative effects of the CVS classes reveal the major radiative warmers and coolers from the
43 perspective of the planet as a whole, the surface, and the atmosphere. Single-layer low clouds
44 dominate planetary and atmospheric cooling, and thermal infrared surface warming. We also
45 investigate the consistency between passive and active views of clouds by providing the CVS
46 breakdowns of MODIS cloud regimes for spatiotemporally coincident MODIS-Aqua (also on the
47 A-Train) and CloudSat-CALIPSO daytime observations. When the analysis is expanded for a
48 more in-depth look at the most heterogeneous of the MODIS cloud regimes, it ultimately
49 confirms previous interpretations of their makeup that did not have the benefit of collocated
50 active observations.

51

52 **1. Introduction**

53 It becomes immediately obvious even to the most casual observer that cloud morphology is
54 rich, variable, and complex. Satellite observations have been essential in our effort to describe
55 and devise measures to quantify a variety of cloud characteristics. Measurements by CloudSat's
56 Cloud Precipitation Radar [CPR, *Stephens et al. 2002*] and CALIPSO's Cloud-Aerosol Lidar with
57 Orthogonal Polarization [CALIOP, *Winker et al. 2010*], both members of the A-Train satellite
58 constellation [*L'Ecuyer and Jiang 2010*], have been instrumental in this effort as they have
59 brought new insights about hydrometeor (cloud and precipitation particles) salient features
60 that remained elusive when relying on only the passive imagers and microwave radiometers at
61 our disposal. In short, these two CloudSat-CALIPSO (CC) active sensors have yielded
62 breakthroughs in our knowledge of hydrometeor vertical variability, structure, and overlap,
63 greatly extending what can be achieved solely with passive sensors [*Chang and Li 2005a,b;*
64 *Joiner et al. 2010; Wind et al. 2010*]. The new information has allowed us to examine, among
65 others: the details of cloud overlap in a manner suitable for parameterization in Large Scale
66 Models [*Barker 2008; Shonk et al. 2010; Oreopoulos et al. 2012*], the contribution of different
67 cloud systems to the radiative heating/cooling profiles of the atmosphere (*Haynes et al. 2013;*
68 *Oreopoulos et al. 2016*), and the (in)consistency between passive and active views of clouds
69 (*Mace and Wrenn 2013; Leinonen et al. 2016*).

70 Following along the lines of previous work (such as *Mace et al. 2009; Li et al. 2015*), this
71 paper also focuses on Cloud Vertical Structure (CVS) as seen jointly by CPR and CALIOP. As
72 explained in *Mace et al. [2009]*, the 94 GHz W-Band CPR can probe rather deeply into
73 hydrometeor layers before being attenuated in the presence of rain, and sometimes has

74 difficulty distinguishing between cloud and precipitation particles. CALIOP, on the other hand, is
75 very sensitive to even thin cloud layers, but cannot probe the details of the atmosphere below
76 clouds of even modest optical thickness (~3 from cloud top). Nevertheless, these two
77 instruments provide jointly the most complete hitherto picture of cloud vertical arrangements.
78 We take advantage of this ability, and aspire to provide a global climatology of CVS, a basic
79 understanding of its main variability features, and why it matters radiatively. We also seek to
80 understand how previous classifications of cloud systems based on passive observations relate
81 to cloud groupings from a CVS perspective. Extracting and analyzing CVS from observations is
82 important for a variety of reasons: (a) It allows us to determine and understand the influence of
83 hydrometeors on the vertical distribution of radiative and latent energy across the globe and
84 hence the atmospheric energy balance; (b) it provides clues about the flux of precipitation
85 throughout the atmosphere; (c) it helps assess the limitations of cloud observations that do not
86 resolve CVS; (d) it provides information that can prove valuable when assessing the realism of
87 cloud simulations in numerical models such as cloud resolving models and Atmospheric General
88 Circulation Models (AGCMs).

89 Because CVS can potentially be complex with many permutations of how distinct cloud
90 layers overlap possible, simplifications are in order. Making the problem manageable is
91 therefore a major aspect of the paper. While our CVS classes are exactly the same as those by
92 *Tselioudis et al. [2013]*, the data product they are obtained from and the derivation method
93 differs from theirs. Similar to that paper, we examine what kind of CVS classes are contained in
94 so-called cloud regimes from passive observations, an exercise that is very illuminating about
95 how different observing systems see the same clouds. Another major aspect of our paper is

96 examining the effect of the different CVS classes on radiative fluxes. Because radiative fluxes
97 are reconstructed from cloud information, investigation of the radiative effects of CVS classes
98 does not have to be limited only to the Top of the Atmosphere (TOA). Rather, we can also
99 determine what the radiative effects of the CVS classes are at the surface and within the
100 atmosphere.

101 Our paper consists of two major parts: (1) global CVS climatology and associated global
102 radiative effects; (2) investigation of the vertical structure (via CVS classes) of the Moderate
103 Resolution Imaging Spectroradiometer (MODIS) cloud regimes of *Oreopoulos et al. [2016]*.
104 These analyses are preceded by a description of how the CVS classes are derived. The
105 assumptions and other details of the derivation are provided separately in an Appendix.
106

107 **2. Datasets and Analysis Methodology**

108 *2.1 CVS class determination*

109 Cloud Vertical Structure (CVS) can be quite intricate with many configurations possible, so
110 distilling its essence into few manageable classes requires a considerable amount of judicious
111 simplifications. We follow on the footsteps of *Tselioudis et al. [2013]*, and use as a backbone the
112 traditional International Satellite Cloud Climatology Project (ISCCP, *Rossow and Gardner 1993*)
113 classification which broadly assigns clouds into one of high (*H*), middle (*M*), and low (*L*) cloud
114 categories based on cloud top location, with 680 hPa and 440 hPa serving as the atmospheric
115 pressure boundaries delineating the three *standard layers* and associated cloud categories. In
116 our case, this simple cloud classification can be modified to overcome ISCCP's limitations since

117 CloudSat and CALIPSO (especially when combined) provide in principle also cloud bottom
118 information, and can distinguish between distinct cloud layers in the vertical.

119 We use four years (2007-2010) of the merged CloudSat/CALIPSO product 2B-CLDCLASS-
120 LIDAR R04 [Sassen and Wang 2012; see also <http://tinyurl.com/2b-cldclass-lidar>] which
121 contains atmospheric profiles with horizontal and vertical resolutions of 1.4×1.8 (km)² and 240
122 m, respectively, and extends from 82°S to 82°N. The information used from 2B-CLDCLASS-LIDAR
123 is the heights of hydrometeor layer top and base in each profile; we consider those equivalent
124 to the vertical locations of the boundaries of individual cloud elements. The aforementioned
125 framework of three standard layers is then used to define the major CVS classes. To make the
126 problem manageable, multiple cloud layers (i.e., separated by clear skies) are not considered as
127 such when co-existing within a standard layer (they are reduced to single-layer); when two or
128 more cloud elements belonging to one of the H, M, L cloud categories co-exist, they can be
129 either contiguous or non-contiguous (separated by clear layers). With the above assumptions,
130 the possible combinations that yield the same tractable set of CVS classes as Tselioudis *et al.*
131 [2013] are (see Fig. 1): single-layer high clouds (H); single-layer middle clouds (M); single-layer
132 low clouds (L); contiguous (or near-contiguous) clouds spanning the 440-680 hPa and <440 hPa
133 standard layers (HxM); contiguous (or near-contiguous) clouds spanning the 440-680 hPa and
134 >680 hPa standard layers (MxL); contiguous (or near-contiguous) clouds spanning all three
135 standard layers (HxMxL); non-contiguous clouds co-occurring in the 440-680 hPa and <440 hPa
136 standard layers (HM); non-contiguous clouds co-occurring in the <440 hPa and >680 hPa
137 standard layers (HL); non-contiguous clouds co-occurring in the 440-680 hPa and >680 hPa
138 standard layers (ML); and finally non-contiguous clouds simultaneously occurring in all three

139 standard layers (HML). These combinations form the 10 CVS “classes” (11 if clear skies are also
140 counted) depicted in Fig. 1. The Appendix describes in more detail how the far more numerous
141 possible permutations of cloud vertical co-occurrence in 2B-CLDCLASS-LIDAR are consolidated
142 into these few classes. Without going into the details that the Appendix exhaustively
143 documents, we should point cloud profiles assigned CVS classes that appear single-layer (H, M,
144 L) or contiguous (H×M, M×L, and H×M×L) in Fig. 1 may in reality be multi-layer in 2B-CLDCLASS-
145 LIDAR according to conventional definitions. This is clearly shown in several example
146 configurations of Figs A2-A4 that are reduced to single-layer (confined to only one standard
147 layer) or contiguous CVS classes because the clear-sky separation of the distinct cloudy layers is
148 not wide enough, i.e., clouds are “near-contiguous” (criteria are described in the Appendix).
149 Our simplifications and the exact meaning of our CVS classes should therefore be taken into
150 consideration when comparing with other studies of CVS.

151 In order to derive the simplified CVS classification, we need information for both the cloud
152 top and cloud base pressures (CTP and CBP, respectively). The 2B-CLDCLASS-LIDAR (as well as
153 all other CloudSat or merged products) provide altitude information in terms of physical height.
154 To convert height to atmospheric pressure we use the ancillary 2B-ECMWF-AUX product. After
155 the conversion from height to pressure has been accomplished, we can proceed to assignment
156 of the CVS class for each observed profile using the scheme described in the Appendix.

157 We must note that we tested several variations of the procedure described in the
158 Appendix, such as different pressure thickness thresholds for distinguishing between thick and
159 thin clouds spanning two or three standard layers, and using CTP instead of the pressure at the
160 geometrical center of the cloud entity to forcibly confine thin clouds spanning two standard

161 layers to a single standard layer. Remarkably, we found that global results were not too
162 sensitive to specific choices. When the assignment of cloud configurations to the CVS classes
163 per the scheme described in the Appendix was completed, we ended up with only 0.5% of
164 cloudy columns (profiles) unassigned because of extreme complexity.

165

166 *2.2 Radiative fluxes*

167 The radiative impact of the different CVS categories is examined with the aid of the coincident
168 2B-FLXHR-LIDAR R04 data [*L'Ecuyer et al. 2008; Henderson et al. 2013; Matus and L'Ecuyer*
169 *2017*]. The impact is measured in terms of the SW and LW Cloud Radiative Effects (CREs),
170 namely the difference between cloudy-sky and clear-sky net (downward minus upward) fluxes
171 at the Top of the Atmosphere (TOA) and Bottom of the Atmosphere (BOA). The SW CREs are
172 highly-dependent on the incoming solar flux at the time of the approximate 1:30 pm local solar
173 time overpass, and are scaled to diurnal fluxes by normalizing with the ratio of the diurnally
174 averaged incoming solar flux at TOA $\overline{F_{SW}^{TOA}}$ to the instantaneous incoming flux at TOA F_{SW}^{TOA} for
175 that location and day of the year [as in *Haynes et al. 2013*]:

$$176 \quad \overline{CRE}_{SW} = CRE_{SW} \left(\frac{\overline{F_{SW}^{TOA}}}{F_{SW}^{TOA}} \right) \quad (1)$$

177 This quantity is negative at both TOA and BOA when CRE is defined in terms of net fluxes,
178 indicating that clouds cool both the Earth-Atmosphere system and the surface in the SW. The
179 LW CREs, which are positive for both TOA and BOA indicating that the cloud thermal infrared
180 (greenhouse) effect warms both the Earth-Atmosphere system and the surface, are not
181 adjusted for diurnal variations (it is not clear or straightforward how to do this, and it matters

182 much less than for the SW). The sum of SW and LW CRE gives the “total” CRE (sometimes
183 referred in the literature as “net” CRE). The difference between total CRE at the TOA and BOA
184 gives the atmospheric (ATM) total CRE, an indicator of radiative warming or cooling.

185

186 2.3 MODIS CRs

187 We also use the MODIS Cloud Regimes (CRs) of *Oreopoulos et al.* [2016], hereafter O16. These
188 come from International Satellite Cloud Climatology Project (ISCCP)-like daily (daytime) joint
189 histograms of CTP and Cloud Optical Thickness (COT). To derive the CRs, the joint histograms
190 from both Terra and Aqua were treated as a single ensemble that was subjected to *k-means*
191 clustering analysis [Rossow et al. 2005] from which 12 global MODIS CRs emerged. Details can
192 be found in O16. The regime centroids (mean of alike histograms) are displayed in Fig. 2 (same
193 as Fig. 1 in O16). In addition, a brief overview of the salient characteristics of each MODIS CR
194 and mean properties is provided in Table 1 (similar to Table 1 in *Oreopoulos et al.* [2017]).

195 In addition to the nominal CRs in O16 we explore internal variability of CR CVS occurrence,
196 by further breaking these CRs into “subregimes” [Mason et al. 2014; Leinonen et al. 2016]. This
197 is accomplished by using the Euclidean distances of CR member histograms from their CR
198 centroid (mean histogram). Specifically, we create three subregimes for each CR by averaging
199 all member histograms that have distances belonging to either the first (1q), the second (2q) or
200 the third (3q) quartile of the distance distribution. There are other ways to create subregimes
201 such as re-clustering all member histograms of a CR, but we found that the simple method
202 based on the quartile grouping of distances produces meaningful distinct subregimes.

203 Moreover, we are mainly interested in the internal variability of a CR's CVS, and examining the
204 problem from the perspective of subregimes is just one of several possible options.

205

206 **3. Global Cloud Vertical Structure**

207 *3.1 Global climatology*

208 Figure 3 shows the global area-weighted relative frequency of occurrence (RFO), in percentage,
209 of the 11 (including clear skies) CVS classes. Since the RFO of a CVS class comes from the ratio
210 of the number of cloudy columns belonging to the class to the total number of columns
211 (appropriately weighted by area), on a global scale it has the same meaning as cloud fraction
212 (CF). The x-axis shows cumulative RFO as CVS classes are added, with the different classes
213 ordered from the highest to the lowest RFO, except for clear skies which is always last and
214 displayed by the gray bar. The RFO of each class corresponds to the difference between
215 cumulative RFO values at the right and left edge of the bar (i.e., width of the bar) representing
216 the class. These global RFOs of each CVS class are also provided in the second column of Table
217 2. Note that the bars occupy the standard layers appropriate for each CVS class, in order to
218 provide appropriate visualization. The bars are wider and connect across layers for contiguous
219 classes ($H \times M$, $M \times L$, $H \times M \times L$).

220 The two most frequent CVS classes represent single-layer (according to our convention,
221 i.e., confined to only one standard layer) cloud configurations: first is CVS="L" which occurs 26%
222 of the time, followed by CVS="H" which occurs about half as often, with a 13.3 % frequency.
223 The remaining single-layer CVS class, CVS="M" is far less frequent and occurs only 3.2% of the
224 time making it the 6th most frequent CVS class. From the two-layer CVS classes with distinct

225 cloud layers, CVS="HL" is the most frequent (\sim 10% RFO, third overall), followed by CVS="HM"
226 (3%) and then CVS="ML" (\sim 2%), while of the two-layer CVS classes with contiguous cloud layers,
227 CVS="MxL" is slightly more frequent (3.5%) than CVS="HxM" (2.9%). When all three standard
228 layers are occupied by clouds, the one with contiguous clouds (as defined in our overlap model)
229 CVS="HxMxL" is far more frequent (fourth overall in frequency, RFO=9.5%) than the one with
230 intervening clear skies between the layers, CVS="HML", which is the most rare CVS class with
231 RFO=1.4%. Finally, clear skies happen \sim 25% of the time.

232 These results support the attention that single-layer "low" and "high" clouds (i.e., our
233 CVS="L" and CVS="H") have previously received in radiation budget studies as cloud
234 configurations with potentially high SW CRE and low LW CRE contributions at the TOA and vice-
235 versa [e.g., *Hartmann et al. 1992*]. This will be more precisely quantified here later. Not only are
236 the CREs at the two distinct parts of the spectrum very different (*H* clouds are usually optically
237 thin, producing small SW CRE), but the combined occurrence of these two single-layer CVS
238 classes reaches 52.7% ($=39.3/(1-0.254)$) of all cloudy cases. *H* clouds overlapping *L* clouds is the
239 third most frequent cloud configuration and has received attention before [*Yuan and*
240 *Oreopoulos 2013*]. Mid-level clouds are also not as rare as commonly believed: they are quite
241 rare globally as single-layer entities (CVS="M" has RFO=3.2%), but can be frequent locally and
242 as part of cloud configurations where they are not connected to clouds in the other two
243 standard layers (according to our convention), namely in CVS classes "ML", "HM", and "HML":
244 when all these classes are considered collectively (along with CVS="M") "isolated" *M* clouds
245 occur about \sim 10% of the time (\sim 13% of cloudy skies). Note that this estimate may deviate

246 substantially from others that use only cloud top height (within a wide range of values) to
247 determine presence of M clouds [e.g., *Zhang et al. 2010*].

248 In the following two sections we will examine how much variability is embedded in these
249 annually-averaged global results. Specifically, we will examine daytime-nighttime differences,
250 land-ocean differences, as well as the seasonal cycle of the zonal RFO distribution of the four
251 most prominent CVS classes.

252

253 *3.2 Daytime-Nighttime differences*

254 Similar to Fig. 3, we now show two panels (Fig. 4a and 4b) of CVS class RFO frequency, but now
255 composited separately from ascending (daytime) and descending (nighttime) observations by
256 the two observational platforms. See also third and fourth column of Table 2 for exact values.

257 The frequency of clear-skies is larger during daytime compared to nighttime (27.4% vs
258 23.3%) and the ordering of CVS classes is also different although it must be noted that relatively
259 small changes in the absolute frequency are sufficient to change the ordering. The largest
260 absolute difference occurs for CVS="HL", with the daytime RFO dropping to 8.7% and making
261 this CVS class slightly less frequent than CVS="HxMxL". Since single-layer L clouds (CVS="L") are
262 actually slightly more numerous for daytime (26.4% vs 25.7%), broadly consistent with *Chepfer*
263 *et al.* [2010] the reduction in CVS="HL" probably comes mostly from H clouds (additional
264 evidence is CVS="H" having RFO=12.7% for daytime vs 13.9% for nighttime). Detection of the
265 thinner of the H clouds may be affected by the varying quality between daytime and nighttime
266 observations—daytime is noisier because of the presence of natural illumination, see *Nazaryan*
267 *et al.* [2008]; *Chepfer et al.* [2010]. Indeed, the larger clear sky fraction of daytime observations

268 seems to be coming from fewer *H* clouds (note that all CVS classes involving *H* clouds have
269 lower RFO in daytime compared to nighttime). When RFOs are normalized to represent
270 percentages of cloudy-skies rather than all-skies, then we see that CVS="L" is even more
271 prevalent during daytime (RFO=36.4% vs 33.5%). The four most prevalent CVS classes represent
272 78.5% of clouds during daytime and 78.2% during nighttime, indicating that almost all of the
273 decrease in the occurrence of clear skies during nighttime comes from cloud fraction increases
274 by CVS="H", CVS="HL" and CVS="HxMxL".

275 For daytime, we can compare our overall percentage of multi-layer occurrences relative to
276 all clouds with that derived from MODIS-Aqua using appropriate information contained in the
277 Level-3 dataset. Specifically, the CF corresponding to clouds on which successful optical
278 property retrievals were performed and which were identified as multi-layer (Wind et al. 2010),
279 can be divided by the CF of all successful retrievals. The global MODIS value of this ratio for our
280 analysis period is ~16%. This is below the combined RFO of ~20% (relative to cloudy skies) of
281 the "HL", "HM", "ML", and "HML" CVS classes during daytime even though these do not include
282 all multi-layer clouds (our simplified scheme reduces the near-contiguous cases to single-layer
283 or contiguous). It is also below the 25% relative multi-layer occurrence obtained by Wang et al.
284 (2016) from MODIS Level-2 data; the discrepancy between the two MODIS values may be due
285 to one of the multi-layer tests being omitted in Level-3 aggregation (Platnick et al. 2016).

286

287 *3.3 Land-Ocean differences*

288 Our exploration of the variability of global CVS continues with an investigation of contrasts
289 between oceanic and continental clouds. We use the land-ocean-coast mask included in the 2B-

290 GEOPROF-LIDAR product [*Mace and Zhang 2014*] for this exercise, with coastal profiles
291 excluded.

292 The two panels of Fig 5 (and the fifth and sixth column of Table 2) reveal that there are
293 very prominent differences between land and ocean. First of all, oceans are much cloudier
294 according to 2B-CLDCLASS-LIDAR with 79.2% global mean CF dwarfing the 63.5% global mean
295 CF of land, as found by *Chepfer et al. [2010]* and consistent with previous climatologies from
296 entirely different types of measurements [e.g., MODIS, *King et al. 2013*]. Second, one sees that
297 the dominance of CVS="L" comes from the ocean where this CVS class occurs almost three
298 times as often as land. Actually, over land CVS="L" ceases to be the leading CVS as it is
299 superseded by CVS="H". If one considers the fraction of these two CVS classes relative to the
300 total amount of clouds in ocean and land, CVS="L" represents 40.5% of oceanic clouds and
301 17.8% of continental clouds, while the figures for CVS="H" are 15.2% and 26.0%, indicating that
302 most of the overall reduction of land CF comes from CVS="L" and that CVS="H" does not nearly
303 compensate, even if in relative terms it occurs almost twice as often over land than ocean when
304 cloudy conditions exist. The other major contributor to the more extensive oceanic cloudiness
305 is CVS="HL" which forms more than twice as often over ocean (somewhat less as a fraction of
306 cloudy only cases). Other notable land-ocean contrasts are CVS="M" being mainly a continental
307 CVS, ranking fourth in strength among its land brethren, while its ocean counterpart is the
308 second rarest CVS; and CVS="HxMxL" ranking fourth over ocean while being third in strength
309 over land despite the two RFOs having the same contribution to the overall cloudiness of
310 oceans and lands.

311

312 3.4 Seasonal and geographical variability of major cloud vertical structures
313 Our analysis so far has shown that the most dominant CVS classes are CVS="L", CVS="H",
314 CVS="HL" and CVS="HxMxL" with the last two having very similar RFOs. These four CVS classes
315 combine for a total RFO of 58.4% which stands for 78.3% of cloud skies. We therefore focus
316 only on these dominant CVS classes to examine joint seasonal and geographical variability of
317 cloud vertical configurations. Fig. 6 shows the results in the form of month-by-month variations
318 of the multi-annual zonal monthly means. These plots then inform us on whether these CVS
319 classes exhibit maxima or minima of occurrence at specific latitudes and parts of the year.

320 CVS="L" (Fig 6a), our most frequent CVS class, appears to be much more prominent in the
321 Southern Hemisphere (SH). This should come as no surprise as we have previously seen that
322 this CVS class is mostly oceanic in nature. A prominent peak can be seen in the subtropics
323 consistent with the presence of marine stratocumulus at those latitudes. The peak occurs
324 during July-August-September-October in agreement with previous studies documenting the
325 seasonal variability of these types of clouds [Oreopoulos and Davies 1993; Norris and Leovy
326 1994]. A second subtropical peak, somewhat more poleward happens during SH summer and is
327 probably associated with the weaker parts of mid-latitude storms intruding northward. Another
328 more typical SH mid-latitude peak associated with storms is found further to the south during
329 the summer months. The Northern Hemisphere (NH) has two peaks for this CVS class near polar
330 latitudes during the spring and autumn months.

331 Panel (b) of Fig. 6 reveals that CVS="H" is mainly a tropical CVS that peaks slightly north of
332 the equator during the April to June period. Something similar is observed for CVS="HL" (Fig.
333 6c) which actually has a peak at almost in the same part of the graph (i.e., same latitude and

334 time of the year). Both of these CVS classes seem therefore to be closely associated with
335 tropical convection. On the other hand, CVS="H×M×L" is associated not only with convection
336 (tropical peak clearly seen in Fig. 6d), but also with mid-latitude storms at both hemispheres,
337 especially during the winter months, although the largest RFO in the SH actually occurs during
338 the spring. Note that many of the near-peak RFOs at both hemispheres occur at locations and
339 times of the year with no solar illumination, so comparisons with cloud observations from
340 reflected solar signals are not possible.

341

342 *3.4 Radiative Effects of Cloud Vertical Structures*

343 Given the strong dependence of thermal emission on temperature, it is obvious that the
344 vertical arrangement of clouds within the atmosphere must have a large effect on the longwave
345 flux at the top and bottom of the atmospheric column. But as we will see shortly, the shortwave
346 radiative effect has also a strong dependence on CVS class. This is because the various classes
347 are associated with systematically different total opacities stemming from differences in
348 vertical extent and the tendency of clouds encountered in the three standard layers to exhibit
349 different physical and optical properties.

350 Fig. 7 gives the global radiative influence of CVS classes according to compositing of 2B-
351 FLHXR-LIDAR data [*L'Ecuyer et al. 2008; Henderson et al. 2013; Matus and L'Ecuyer 2017*]. For
352 every profile in 2B-CLDCLASS-LIDAR that was assigned a CVS class we extract the radiative
353 fluxes from 2B-FLHXR-LIDAR and calculate area-weighted means per CVS class. What Fig. 7
354 specifically shows is the TOA and BOA mean CREs (calculated from net=down-up fluxes) for
355 each CVS class for both SW (red bars) and LW (blue bars). Also shown in the middle of the graph

356 is the total atmospheric CRE calculated as the difference between the TOA total (=SW+LW) and
357 BOA total CREs.

358 Figure 7 immediately reveals the wide range of SW and LW CRE values at both the TOA
359 and BOA. While the SW CRE varies greatly among the CVS classes, it is at the same time
360 apparent that the TOA and BOA (surface) components have rather similar values. BOA values
361 are slightly larger because of clouds providing a small amount of additional absorption to the
362 atmospheric column (the additional absorption by the cloud particles exceeds overall the
363 reduced water vapor absorption at the lower atmosphere due to inhibited solar irradiance). The
364 largest SW CRE corresponds not surprisingly to the CVS structure expected to contain most
365 often the optically thickest clouds, CVS="HxMxL". Next comes CVS="HML" which also contains
366 clouds in all three standard layers, and is therefore also likely to be opaque.

367 Contrary to the SW, the LW CRE values can be vastly different at TOA and BOA depending
368 on CVS class. For example, CVS="L" produces little LW TOA CRE because low clouds change the
369 effective height of emission to space very little compared to a clear atmosphere, but affect
370 greatly the LW flux toward the surface because these clouds greatly increase the infrared
371 opacity of the lower atmosphere. On the other hand, CVS classes containing *H* clouds have high
372 LW TOA CRE, but the magnitude of their BOA CRE is modulated by the co-occurrence of clouds
373 in other standard layers; contrast for example CVS="H" with CVS="HML".

374 The dependence of total atmospheric CRE on CVS class is also very intriguing. This
375 radiative quantity tells us whether clouds provide an overall cooling (negative CRE value) or
376 warming (positive CRE value) to the atmospheric column as a whole. The middle part of Fig. 7
377 reveals which CVS classes enhance the radiative cooling of the clear atmosphere (blue shade)

378 and which work alongside latent heating due to condensation to mitigate it (red shade). We see
 379 that only three CVS classes are radiative coolers and all of them contain L clouds, with CVS="L"
 380 providing the strongest cooling. Adding M clouds reduces the cooling, and actually CVS="M"
 381 achieves an almost exact balance between radiative cooling and warming for the atmosphere
 382 as a whole, and is therefore not assigned a color shade; cooling and warming may nevertheless
 383 occur at different altitudes. For a CVS class to be a radiative warmer of the atmosphere it must
 384 have H clouds. When L clouds co-occur with H clouds, the radiative heating generally weakens:
 385 from the six CVS classes that are radiative warmers, CVS="HL" and CVS="HML" are the weakest.
 386 The exception is our most vertically extensive CVS class, CVS="HxMxL", which is the second
 387 strongest radiative warmer. Note that CVS="H" has neither the strongest LW TOA CRE, nor the
 388 strongest ATM total CRE. Additional cloud opacity in the form of M clouds is needed to make
 389 these CREs stronger, with the largest magnitudes achieved by CVS="HxM".

390 While Fig. 7 shows the mean magnitude of the radiative impact of the different CVS
 391 classes when they occur, the overall radiative importance of each CVS class depends on its
 392 frequency of occurrence. We try to convey this in Table 3 which shows the percentage radiative
 393 contribution of each CVS class to the global CRE for four CRE components, calculated as the
 394 ratio of the area-weighted sum of all CRE values for the particular CVS class to the area-
 395 weighted sum of all valid CRE values regardless of CVS class:

$$396 \text{contribution}(\%)_{\text{CRE_CVS}_j} = \frac{\sum_{i=1}^{N_j} w_i \text{CRE}_i}{\sum_{k=1}^{10} \sum_{i=1}^{N_k} w_i \text{CRE}_i} \times 100 \quad (2)$$

397 N_j is the number of profiles corresponding to CVS_j , N_k is the number of profiles corresponding
 398 to CVS_k , and w_i is the weight (=cosine of latitude) for profile i .

399 The contribution to the total ATM CRE is shown differently because its sum over all CVS
 400 classes is a small value due to cancellations between positive and negative CREs (specifically, it
 401 is 6.3 Wm^{-2} , close to the *Henderson et al. 2013* and *Matus and L'Ecuyer 2017*); instead of
 402 percentages we show the contribution in Wm^{-2} of each CVS class calculated as the ratio of the
 403 area-weighted sum of total ATM CRE values, for the CVS class of interest, to the sum of area
 404 weights of all CVS class occurrences:

$$405 \quad contribution_CRE_{TOT_CVS_j}^{ATM} = \frac{\sum_{i=1}^{N_j} w_i CRE_{iTOT}^{ATM}}{\sum_{k=1}^{10} \sum_{i=1}^{N_k} w_i} \quad (3)$$

406 In other words, the numbers in the last column of Table 3 derived from Eq. (3) add up to 6.3 Wm^{-2} . The results from eq. (3) are slightly different from those obtained by multiplying the
 407 area-weighted mean total ATM CRE of a CVS class (Fig. 7) with its area-weighted RFO (2nd
 408 column of Table 3).

410 For the SW CRE, we see (Table 3) that TOA and BOA are virtually the same because the
 411 mean values differ by a small amount that remains relatively constant. CVS="L" rises to the top
 412 as the strongest SW CRE contributor because of its large RFO, even though its mean CRE values
 413 are nowhere near the strongest. CVS="HxMxL" is actually the CVS class with the strongest
 414 mean SW CRE values, but comes second because it ranks only fourth in RFO. In the LW, we saw
 415 earlier the TOA and BOA CRE values are very different and this carries to the contributions. At
 416 TOA, CVS="HxMxL" ranks as the strongest contributor at ~31%, combining the second strongest
 417 mean value with the fourth largest RFO. CVS="HxM" has a slightly stronger mean value, but
 418 because its RFO is only ~3%, it reaches only about a third the contribution of CVS="HxMxL".
 419 While *L* clouds are often ignored in LW CRE discussions because we usually focus on radiative

420 impacts at TOA, Table 3 makes clear that they are (at least in the form of CVS="L") by far the
421 strongest contributor to surface thermal infrared warming with ~40% contribution. This CVS
422 class while not having the strongest mean value of LW BOA CRE, occurs so often that in the end
423 assumes an extremely important role in the LW surface radiation budget.

424 Finally, the great role of RFO in assessing radiative importance reveals itself conspicuously
425 for total ATM CRE (Table 3). The major contributors are three of the four CVS classes with the
426 highest RFOs, namely CVS="L", CVS="H", and CVS="HxMxL". On the flipside, a high RFO by itself
427 does not make a CVS class a large contributor: CVS="HL" is third most frequent, but the mean
428 total ATM CRE is only ~5 Wm⁻², making it contribute only ~0.6 Wm⁻² to the global value which
429 may seem like a respectable ~10% contribution, until we realize that it represents only ~4% of
430 the overall warming contribution (the sum of positive total CRE ATM values).

431

432 **4. Cloud Vertical Structures of MODIS Cloud Regimes**

433 The analysis shown here is in the same vein as that by *Tselioudis et al. [2013]* for ISCCP Weather
434 States. Although derived using a different methodology and dataset, our CVS classes are the
435 same as in that paper and serve the same ultimate goal: to further understand and validate the
436 robustness and meaningfulness of cloud systems classified into regimes by grouping together
437 similar co-variations of cloud properties derived from passive satellite observations.

438

439 *4.1 Nominal MODIS CRs*

440 Fig. 8 shows the breakdown of each of O16's MODIS CRs by CVS class. To achieve the
441 spatiotemporal matching necessary to perform the analysis only Aqua CR occurrences and

442 daytime 2B-CLDCLASS-LIDAR data are used (since CRs can be determined only during daytime).
443 Previous interpretations of the nature of MODIS CRs based on centroid appearance and the
444 most prevalent location of CR members (see Table 1) are largely consistent with the
445 composition by CVS class as we detail below.

446 CR1 has been interpreted as being mainly a tropical regime with the largest fraction of
447 cirrus clouds, but also many vertically developed clouds from convective activity. The CVS
448 breakdown shows CVS="H" dominating (RFO~50%) followed by CVS="HL"; these two classes
449 make up about 77% of CR1. If CVS="HxMxL" is used in this case as a surrogate of deep
450 convective towers, then they occur about 13% of the time within CR1, and it certainly appears
451 that they are accompanied by plentiful cirrus anvils (CVS="H"). CR2 was described in O16 as
452 containing tropical and frontal convection, and the breakdown by CVS class seems to confirm
453 this with CVS="HxMxL" RFO exceeding 60%. While CVS="HxM" is not very important globally, it
454 is a significant contributor to CR2 with an RFO of ~13%. As with CR1, almost all of CR2 consists
455 of CVS classes containing *H* clouds. CR3 shares features with both CR1 and CR2, having CVS="H"
456 and CVS="HL" as the dominant class (similar to CR1), but also having substantial amounts of
457 CVS="HxMxL" and CVS="HxM", similar to CR2.

458 CR4 and CR5 were previously linked to mid-latitude storms, with CR4 containing more
459 optically thick clouds, something that is reflected in the CVS class breakdown with ~20% higher
460 RFO in CVS="HxMxL" than CR5. While CR4 has virtually no CVS="H", for CR5 this class is the
461 third most frequent, and a likely a reason for the lower mean COT (Table 1), along with
462 CVS="HxM" which is rarer in CR4. Note also that CR4 and CR5 are the regimes with the highest
463 RFO of the very rare globally CVS="HML" which occurs almost exclusively within CR2-5. The

464 centroid of CR6 (Fig. 2) has prompted us to identify this regime as the most “mid-level cloud”
465 regime because of the histogram peak within the 440-680 hPa standard layer. Active
466 observations confirm this, with the globally rare CVS=“M” having an RFO of ~16% within that CR
467 (incidentally, CR4 and CR5 also have substantial amounts of this CVS class). CR6 also has high
468 RFOs for the two other classes with unobscured (from space) *M* clouds, CVS=“M×L” and
469 CVS=“ML”, with the former being actually the most dominant CVS class within CR6.

470 Moving on now to CRs dominated by liquid clouds, we see an abrupt transition in CVS
471 morphology from CR6 to CR7. CR7 is dominated by CVS=“L” and the RFO of this class (~70%)
472 remains approximately the same in CR8 and CR9 as well. So, these three regimes are largely
473 single-layer regimes. CVS=“L” RFO progressively drops in CR10 (still about 60% of the time),
474 CR11 and CR12, and these reductions accompany an overall decrease in CF. All regimes from
475 CR7 to CR11 have CVS=“HL” as the second most important CVS class indicating that *H* clouds
476 over *L* clouds is a rather frequent overlap configuration that has justifiably received attention in
477 the past [*Yuan and Oreopoulos 2013*]. The most frequent regime with the lowest CF, CR12, is
478 quite complex in terms of CVS class breakdown. It seems to consist of both CVS=“H” and
479 CVS=“L”, but also their combination, CVS=“HL”. It will be discussed further in the next
480 subsection.

481 Finally, it is important to point out that the CF of CR10, CR11 and CR12 differs
482 considerably between MODIS and CloudSat/CALIPSO, with the difference being quite dramatic
483 for CR12. It appears then that CR12 contains numerous small and optically thin elements that
484 remain undetected by MODIS, but produce strong enough backscatter signals for CALIPSO’S
485 CALIOP lidar to discern from the atmospheric background [*Wang et al. 2016*].

486 4.2 MODIS subregimes

487 While by construction a CR represents an ensemble of joint CTP-COT histograms that are alike,

488 individual member histograms belonging to the same CR may still be quite different. The fact

489 that they were assigned to the same CR simply means that they were even more distinct from

490 histograms that ended up assigned to other CRs. Within the set of histograms that make up a

491 CR we can identify subsets whose members are *even more alike*. We call the ensemble means

492 of these subsets “subregimes” [Mason *et al.* 2014]. Different options to define subregimes are

493 available. Here we adopt the method previously used by Leinonen *et al.* [2016] which is based

494 on quartiles of Euclidean Distance (ED) from the CR centroid as described in subsection 2.3. The

495 objective in this subsection is to compare the CVS composition of subregimes for the four CRs

496 exhibiting the most dramatic CVS contrast between 1q and 3q subregimes (the 2q subregime as

497 an ensemble average of histograms with close-to-median EDs is resembling closely its centroid).

498 The regimes selected for the analysis shown in Fig. 9 are CR1, CR5, CR6, and CR12.

499 Our simple subregime identification procedure produces a CR1_{3q} with a large RFO of

500 CVS=“H×M×L” which seems to have grown at the expense of CVS=“H”. CR1_{1q} has more CVS=“H”

501 and less CVS=“H×M×L” than the centroid (Fig. 8). So, our simple subregime definition has

502 sufficient skill to separate the histograms containing the most convective elements of the

503 regime. The two 3q and 1q subregimes of CR5 are also very different with regard to their

504 vertically extensive clouds represented by CVS=“H×M×L”. Moreover, CR5_{1q} has CVS=“H” as the

505 second most frequent class, while for CR5_{3q} this class is encountered much less (fourth overall).

506 In general, the RFOs of different CVS classes are more evenly distributed in CR5_{1q}: notice that it

507 takes four CVS classes to reach a cumulative RFO of ~63% for CR5_{1q} while it takes only two for

508 CR5_{3q}. The breakdown of CR6 into subregimes reveals that more CVS="M" comes from the
509 histograms with smaller Euclidean distances from the centroid (1q) (and also smaller overall
510 CFs). CR6_{1q} has fewer occurrences of all other major CVS classes within this regime (CVS="L",
511 "M×L", "H×M×L").

512 The breakdown into subregimes and reconstruction of CVS partitioning becomes even
513 most interesting for CR12 (Fig. 9d). The two subregimes are completely different in terms of
514 cloud fraction, with CR12_{1q} made almost exclusively by low fraction (RFO) single layer clouds
515 CVS="L", complemented by CVS="H". The much more cloudy CR12_{3q}, on the other hand, has in
516 addition to those two CVS classes also substantial amounts of CVS="HL" and CVS="H×M×L". The
517 presence of the latter class, as well of CVS="H×M" explains CR12_{3q}'s considerable precipitation
518 production (according to our own analysis not shown here) and justifies the inclusion of the
519 parent CR12 in the group of CRs for which invigoration is investigated [Oreopoulos *et al.* 2017].

520

521 **5. Summary and Conclusions**

522 We have performed a comprehensive analysis of cloud vertical structure (CVS) at global scales
523 using a product (2B-CLDCLASS-LIDAR) that combines observations from active space-based
524 sensors, namely the CALIOP lidar aboard the CALIPSO satellite and the CPR radar aboard the
525 CloudSat satellite. These satellites and instruments fly in formation as part of the A-Train
526 constellation and therefore make contemporaneous collocated observations. Moreover, their
527 measurements can also be collocated with those by the MODIS instrument aboard the Aqua
528 satellite, also part of the A-Train, something we also take advantage of in this study.

529 We have attempted to capture the richness of CVS with minimal sacrifice in information
530 content, by reducing complex cloud configurations into a few intuitive vertical arrangements
531 (CVS “classes”) where clouds in a particular vertical profile occupy either one, two or three
532 standard vertical layers. We found that CVS classes previously defined by *Tselioudis et al.* [2013]
533 are suitable for this purpose, even though a different dataset and methodology was used to
534 derive them in that effort.

535 Our study makes a significant contribution to the knowledge of global cloudiness. We
536 determined which cloud vertical configurations are more frequent at global scales (single layer
537 low, CVS=“L”, and high clouds, CVS=“H” represent ~53% of cloudy skies) and whether the
538 frequencies of the CVS classes differ substantially when examined separately for daytime versus
539 nighttime (~4% more clouds overall in the latter case, but with the occurrence order of the CVS
540 classes affected only in minor ways), and land versus ocean (the dominance of CVS=“L” was
541 found to overwhelmingly come from ocean occurrences). The seasonal and geographical
542 variations of the four most dominant CVS classes are substantial, with easily discernible
543 patterns consistent with our understanding of global circulation and weather systems.

544 We also have added to our understanding of how different cloud systems affect the
545 radiation budget, previously examined in terms of cloud type [*Hartmann et al.* 1992; *Chen et al.*
546 2000], cloud phase [*Matus and L'Ecuyer* 2017], and cloud regime [*Haynes et al.* 2011;
547 *Oreopoulos and Rossow* 2011; *Tselioudis et al.* 2013; *Oreopoulos et al.* 2014; *Oreopoulos et al.*
548 2016]. This study adds a piece to the puzzle by providing cloud radiative impact based on
549 vertical configuration classification. We show which CVS classes have strong, moderate, or
550 weak impacts on TOA, surface and atmospheric radiation budgets using as criteria either mean

551 instantaneous magnitudes or overall contributions. We found, for example, that single-layer
552 low clouds (CVS="L") dominate planetary and atmospheric cooling, and thermal infrared
553 surface warming; the vertically extensive cloud configuration (CVS="HxMxL"), despite being
554 only the fourth most frequent CVS class, is either first or second in radiative importance for
555 both the solar and the thermal infrared regardless of whether one focuses on the planet as a
556 whole (TOA), the surface, or the atmosphere.

557 We also looked closely at how passive and active cloud observations compare. Previously
558 defined cloud regimes derived from MODIS cloud optical thickness and cloud top pressure co-
559 variations were probed in terms of their internal distribution of CVS classes and were shown to
560 have considerable amounts of internal variability. Reassuringly, our analysis also revealed that
561 the interpretations of the nature of the MODIS regimes were largely on target, a conclusion
562 that complements the findings of *Leinonen et al.* [2016] which were based exclusively on
563 comparisons with CloudSat CPR reflectivities.

564 Although the path to replicate our CVS classification in AGCMs is not obvious, and may
565 require more sophisticated subcolumn cloud generators than currently available in order to
566 create credible subgrid cloud variability, we hope that cloud validation in this class of models
567 will now have an additional aspect of cloud morphology to consider.

568

569 **Acknowledgements**

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571 MODIS cloud regimes used in this study can be provided by the lead author upon request.
572 Other MODIS datasets can be obtained at <https://ladsweb.modaps.eosdis.nasa.gov/search/>.

573 CloudSat datasets can be obtained at <http://www.cloudsat.cira.colostate.edu>. We thank our
574 colleagues Kerry Meyer and Steven. E. Platnick for helpful discussions about MODIS products.

575

576 **Appendix**

577 We provide here details of how the cloud vertical stratification extracted from 2B-CLDCLASS-

578 LIDAR was condensed into the 10 cloudy CVS classes of *Tselioudis et al.* [2013].

579 (1) *Single contiguous cloud*. When a single contiguous cloud is identified in 2B-CLDCLASS-LIDAR

580 (47.4% of available profiles, Fig A1), possible scenarios are [CTP=Cloud Top Pressure;

581 CBP=Cloud Bottom Pressure]:

582 a. The cloud is confined to one of the three standard layers: if [CTP and CBP \leq 440 hPa]

583 then CVS = "H"; if [CTP and CBP > 440 hPa] and [CTP and CBP \leq 680 hPa] then

584 CVS="M"; if [CTP and CBP > 680 hPa] then CVS="L" (see Fig. A1, case (a)).

585 b. The cloud spans two standard layers (Fig. A1, case (b)): there are two possibilities,

586 CTP \leq 440 hPa and 440 hPa < CBP \leq 680 hPa in which case the default is CVS="HxM";

587 and 680 hPa < CTP \leq 440 hPa and CBP > 680 hPa in which case the default is

588 CVS="MxL". The default case applies when the cloud is "thick", defined as CBP-CTP \geq

589 200 hPa (note that our analysis examines cloud thickness only when the cloud spans

590 two or three standard layers, i.e., crosses standard layer boundaries). Otherwise

591 (CBP-CTP < 200 hPa, cloud is thin), the CVS = "HxM" class can revert to either

592 CVS="H" or CVS="M", while the CVS="MxL" can revert to either CVS="M" or

593 CVS="L". This re-classification to a single-layer CVS category depends on the

594 pressure of the cloud's geometric center location determined by logarithmic

595 averaging of CTP and CBP. If the center location falls within the top standard layer

596 then CVS="H", if it falls within the middle standard layer then CVS="M", and if it falls

597 within the bottom standard layer then CVS="L". The re-assignment of "thin" clouds

598 crossing standard layer boundaries to a CVS class representing a single cloud layer
599 deviates from the ISCCP approach of assigning clouds to standard layers according to
600 CTP. Now that we have additional information on CBP in our disposal, our
601 philosophy is to make the assignment based on where the bulk of the “thin” cloud
602 resides.

603 c. If the cloud spans all three standard layers (Fig. A1, case (c)), i.e., [CTP \leq 440 hPa and
604 CBP > 680 hPa] and is “thick”, defined as CBP-CTP \geq 440 hPa (=pressure thickness of
605 the standard middle layer + 200 hPa as before) then the cloud is assigned to the
606 default CVS=“HxMxL” category. When the cloud is “thin”, i.e., CBP-CTP < 440 hPa,
607 then its presence in one or two of the standard layers may be small, so that
608 CVS=“HxMxL” reverts to CVS=“HxM” when CTP < 340 (=440-100) hPa (not much
609 cloud resides in the bottom standard layer), to CVS=“MxL” when CBP > 780
610 (=680+100) hPa (not much cloud resides in the top standard layer), and to CVS=“M”
611 when the cloud is “thin” and none of the other conditions apply.

612 (2) *Two distinct cloud layers*. When two distinct layers of cloud are identified in 2B-CLDCLASS-
613 LIDAR (20.5% of profiles, Figs. A2, A3), possible scenarios are:

- 614 a. The top and bottom of *both* cloud layers are confined within one of the standard
615 layers. Then the two cloud layers within the standard layer are considered single
616 layer clouds for our purposes, resulting in one of CVS=“H”, CVS=“M”, CVS=“L” (Fig.
617 A2, case (a)).
- 618 b. Each of the two cloud layers is confined to a *different* standard layer. The CVS class is
619 then one of the three possible classes that indicate separate (non-contiguous) cloud

620 layers each belonging to a different cloud category. Namely, CVS="HM", CVS="HL",
621 or CVS="ML" (Fig. A2, case (b)).

622 c. One of the cloud layers spans two standard layers while the other is confined to a
623 single standard layer. Now there are two possibilities:

624 i. The two cloud layers have a common standard layer, for example the
625 topmost cloud is "H" while the cloud below is "H×M" (abbreviated here as
626 [H, H×M]); if the "H×M" is thick (CBP-CTP ≥ 200 hPa) then it is considered
627 merged with the "H" cloud resulting in CVS="H×M". On the other hand, if the
628 "H×M" layer is "thin", then we calculate the location of the cloud center as
629 before by taking the logarithmic average of its CTP and CBP, and reduce it to
630 a cloud that is confined to a single standard layer, i.e, either "H" or "M"; in
631 the former case, CVS="H" (cloud merging), while in the latter case CVS="HM"
632 (Fig. A2, case (c(i))). Other possible cases (not illustrated) in this type of
633 scenario are: [H×M,M] which can result in CVS="H×M" when the highest
634 cloud H×M is thick (merge with "M"), or CVS="HM" or CVS="M" for the cases
635 of thin H×M clouds with different geometric centers; [M×L,L] similarly yields
636 either CVS="M×L" (thick M×L cloud) or CVS="ML" or CVS="L"; [M,M×L] yields
637 either CVS= "M×L" (thick M×L cloud) or CVS="ML" or CVS="M".

638 ii. The cloud layers do not have a common standard layer: Two cases are now
639 possible. One case is [H,M×L] which becomes CVS="H×M×L" when the
640 bottom M×L cloud is thick, or CVS="HM" or CVS="HL" when the bottom
641 cloud is thin, depending on the standard layer its geometric center falls into

642 (Fig. A2, case (c(ii))); the other case is [H×M,L] (not illustrated) which yields
643 either CVS="H×M×L" (thick H×M cloud) or CVS="HL" (thin H×M cloud whose
644 center is in top standard layer) or CVS="ML" (thin H×M cloud whose center is
645 in middle standard layer).

646 d. Each of the cloud layers spans two standard layers, namely [H×M, M×L] (Fig. A3, case
647 (d)). If both layers are thick then CVS="H×M×L". If both layers are thin then we look
648 at cloud center locations: if both fall in the middle standard layer then CVS="M" or
649 they can be in different standard layers, resulting in one of CVS="HM", CVS="HL",
650 CVS="ML". If the H×M cloud is thick and the M×L cloud is thin then CVS="H×M×L"
651 when the center of the lower cloud is located within the lowest standard layer, while
652 CVS="H×M" when its center is located in the middle standard layer (cloud merging in
653 both cases). If on the other hand the H×M cloud is thin and the M×L cloud is thick
654 then the center location of the top cloud determines the final CVS outcome:
655 CVS="H×M×L" results when the center is in the topmost standard layer, while CVS=
656 "M×L" when the center resides in the middle standard layer.

657 e. One of the cloud layers spans three standard layers while the other is confined to a
658 single standard layer, namely the cloud configuration is either [H, H×M×L] (Fig. A3,
659 case (e)) or [H×M×L, L] (not illustrated). In this case we examine the thickness of the
660 H×M×L cloud layer using the 440 hPa threshold as before. For both configurations,
661 when the H×M×L cloud layer is thick then CVS="H×M×L". If the H×M×L cloud is thin
662 on the other hand we examine the center location according to the description in 1c
663 and the cloud is reduced to either "M", or "H×M", or "M×L". When these clouds are

664 combined with the H cloud of the [H, H×M×L] configuration, possible CVS outcomes
665 are, respectively, CVS="HM", CVS="H×M", CVS="H×M×L" (Fig. A3, case (e)), while
666 when they are combined with the L cloud of the [H×M×L, L] configuration, then one
667 of CVS="ML", CVS="H×M×L", CVS="M×L" will be the final outcome (not shown).

668 (3) *Three distinct cloud layers.* When three distinct layers of clouds are identified in 2B-
669 CLDCLASS-LIDAR (5.8% of profiles) there are 78 possible configurations for our simplified
670 cloud overlap model, with broad scenarios being:

671 a. The top and bottom of *all three* cloud layers are confined within one of the standard
672 layers. Then the three cloud layers within the standard layer are considered as a
673 single layer (cloud merging), resulting in CVS="H", or CVS="M", or CVS="L" (Fig. A4,
674 case (a)).

675 b. Each of the three cloud layers is confined to a *different* standard layer. Then
676 CVS="HML" (Fig. A4, case (b)).

677 c. Two of the three cloud layers are confined within one standard layer while the third
678 layer is confined to a *different* standard layer (Fig. A4, case(c)). Possible CVS
679 outcomes in this case are: CVS="HM" for either two cloud layers in the top standard
680 layer and one in the middle standard layer, or for one cloud layer in the top standard
681 layer and two in the middle standard layer; CVS="HL" for either two cloud layers in
682 the top standard layer and one in the bottom standard layer, or for one cloud layer
683 in the top standard layer and two in the bottom standard layer; CVS="ML" for either
684 two cloud layers in the middle standard layer and one in the bottom standard layer,

685 or for one cloud layer in the middle standard layer and two in the bottom standard
686 layer.

687 d. One of the three cloud layers spans two or three standard layers (not illustrated).

688 There are now too many scenarios to describe, but the gist is that to arrive at one of
689 our 10 CVS classes we follow on the footsteps of what was done in our previous
690 simpler configurations. Basically, we examine whether the cloud crossing standard
691 layer boundaries is thick or thin and apply the logic described earlier. If the cloud
692 crosses two boundaries (spans three standard layers) and is thick (≥ 440 hPa), then
693 CVS="HxMxL"; if it's thin, it is reduced using the center location calculation
694 described above to a cloud spanning two standard layers, and the eventual CVS
695 outcome depends on whether this cloud shares a common standard layer with the
696 remaining cloud layer.

697 e. Two of the three cloud layers span two standard layers. Again, there are numerous
698 permutations, but the CVS assignment can be done using rules already established
699 previously. CVS="HxMxL" is a frequent outcome, as expected, if both or even one of
700 the clouds spanning the two standard layers is thick (≥ 200 hPa), depending also on
701 the location of the other cloud layer. But CVS classes indicating non-contiguous
702 clouds are also possible, especially when both cloud layers crossing standard layer
703 boundaries are thin.

704 (4) *Four or more distinct cloud layers.* When four or more distinct cloud layers exist (only 0.9%
705 of profiles), then we derive CVS classes only for the simpler cases where the cloud entities

706 do not cross standard layer boundaries, using the concepts and logic described above (0.4%
707 of profiles).

708 Applying all the above assigns the vast majority of cloud vertical configurations in a given
709 profile, with only a small fraction (0.5% of the overall cloudy columns) being too complex for
710 CVS derivation, and therefore discarded.

711

712 **List of Tables**
 713 **Table 1.** Brief description and globally-averaged properties of the 12 MODIS CRs introduced by
 714 *Oreopoulos et al. [2016]* and used in this study. The CF is weighted by area, so is slightly
 715 different from that of Fig. 2 which corresponds to the sum of the bin CFs within the centroids.

| CR | Description | RFO (%) | CF (%) | Mean COT | Mean CTP (hPa) |
|------|---|---------|--------|----------|----------------|
| CR1 | Mostly tropical with a pronounced presence in the Pacific ocean, and elsewhere within the confines of ITCZ. Contains a lot of the tropical cirrus associated with convection, but also deeper convective clouds. | 3.46 | 84.0 | 9.9 | 292 |
| CR2 | Contains most of the optically thickest and tallest clouds of all CRs; includes storm systems produced by tropical and frontal convection and has the highest CF of all regimes. | 2.99 | 96.6 | 23.4 | 354 |
| CR3 | Tracks tightly the geographical pattern of CR2, but contains the thinner elements of storm activity. | 5.02 | 89.0 | 7.7 | 369 |
| CR4 | Extratropical and dominated by alto- and nimbo- type clouds in higher latitude storm systems. More prevalent during the summer months. | 3.77 | 92.5 | 25.8 | 477 |
| CR5 | Closely associated with CR4, but with fewer optically thick clouds and more prevalence during the winter months. | 3.68 | 86.5 | 10.9 | 490 |
| CR6 | Contains proportionally the most mid-level clouds and also has some congestus, with strong land presence. | 6.99 | 83.2 | 22.3 | 602 |
| CR7 | Mainly a high latitude CR of plentiful thick stratus over both land and ocean with small RFO and big CF. | 2.44 | 95.7 | 26.8 | 721 |
| CR8 | Boundary layer regime with occurrence peaks in known marine stratocumulus areas, but additional presence in far southern oceans and northern lands. | 4.92 | 86.7 | 12.9 | 738 |
| CR9 | Similar to CR8 in CF, but of a more marine character and with shallower and optically thinner clouds; presence also peaks in known marine stratocumulus areas. | 7.62 | 91.1 | 13.9 | 821 |
| CR10 | Also as marine as CR9, but with lower CF indicating greater relative presence of broken stratocumulus and shallow cumulus. | 7.28 | 68.3 | 6.6 | 817 |
| CR11 | Even more broken stratocumulus and shallow cumulus than CR10, with small optical thicknesses and low cloud fractions; almost exclusively oceanic with negligible presence in high latitudes. | 10.36 | 50.3 | 4.6 | 836 |
| CR12 | Comprises all 2D histograms with no characteristic shape, or histograms with a dipole pattern where high clouds overlap low clouds; has the highest global RFO and smallest CF, and except the nearly always overcast far southern oceans, is nearly omnipresent. | 41.47 | 29.3 | 11.9 | 705 |

716

717 **Table 2.** Area-weighted Relative Frequency of Occurrence (RFO, in %) of the different CVS
 718 classes, ordered from highest to lowest by the global RFO of each class (second column). The
 719 remaining columns show special situations, namely global RFOs for daytime only, nighttime
 720 only, ocean only, and land only observations.

721

| CVS class | Daily | Daytime | Nighttime | Ocean | Land |
|-----------|-------|---------|-----------|-------|------|
| L | 26.0 | 26.4 | 25.7 | 32.1 | 11.3 |
| H | 13.3 | 12.7 | 13.9 | 12.0 | 16.5 |
| HL | 9.7 | 8.7 | 10.6 | 11.4 | 5.5 |
| HxMxL | 9.5 | 9.2 | 9.8 | 10.0 | 8.1 |
| MxL | 3.5 | 3.5 | 3.5 | 3.6 | 3.2 |
| M | 3.2 | 3.3 | 3.2 | 1.9 | 6.6 |
| HM | 3.0 | 2.6 | 3.5 | 2.1 | 5.3 |
| HxM | 2.9 | 2.9 | 2.9 | 2.4 | 4.2 |
| ML | 2.2 | 2.2 | 2.1 | 2.3 | 1.7 |
| HML | 1.4 | 1.2 | 1.5 | 1.4 | 1.2 |
| Clear | 25.4 | 27.4 | 23.3 | 20.8 | 36.5 |

722

723 **Table 3.** Percentage contributions of the different CVS classes to different CRE components
 724 (columns SWTOA, LWTOA, SWBOA, LWBOA). The last column represents the Wm^{-2} contribution
 725 of each CVS class (Eq. 3) to the global total ATM CRE of 6.3 Wm^{-2} .

726

| CVS class | RFO | SWTOA | LWTOA | SWBOA | LWBOA | totATM |
|-----------|------|-------|-------|-------|-------|--------|
| L | 26.0 | 31.2 | 9.9 | 31.1 | 39.7 | -8.9 |
| H | 13.3 | 4.2 | 20.1 | 4.3 | 4.0 | 6.2 |
| HL | 9.7 | 10.3 | 10.4 | 10.3 | 10.3 | 0.6 |
| HxMxL | 9.5 | 26.2 | 31.3 | 26.4 | 18.7 | 6.3 |
| MxL | 3.5 | 7.5 | 4.8 | 7.6 | 8.7 | -0.9 |
| M | 3.2 | 4.3 | 4.0 | 4.2 | 4.6 | 0.0 |
| HM | 3.0 | 4.4 | 5.2 | 4.2 | 3.1 | 0.9 |
| HxM | 2.9 | 5.0 | 9.7 | 5.1 | 4.4 | 2.3 |
| ML | 2.2 | 4.2 | 2.4 | 4.1 | 4.3 | -0.5 |
| HML | 1.4 | 2.8 | 2.2 | 2.7 | 2.1 | 0.2 |

727

728

729 **List of Figures**

730 **Figure 1.** Graphical illustration of our 10 CVS classes based on the details of the vertical
731 stratification of clouds in the three standard atmospheric layers.

732 **Figure 2.** The centroids (average joint histograms) that define the MODIS Global Cloud Regimes
733 used in one of the main components of this study. These regimes were introduced by O16.
734 Above each panel we show the global averages of Relative Frequency of Occurrence (RFO, in %,
735 as defined in O16) and Cloud Fraction (CF, in %).

736 **Figure 3.** Area-weighted RFOs of the various CVS classes plotted in cumulative form using bars
737 that occupy the standard layers relevant to each class and have widths corresponding to each
738 CVS class RFO in % (values also provided in second column of Table 2). The CVS classes are
739 ordered from the largest to the smallest RFO. The gray bar indicates clear skies.

740 **Figure 4.** As in Fig. 3, but now separately for daytime (ascending node, panel (a)) and nighttime
741 (descending node, panel (b)) conditions. Individual CVS class RFOs are also provided in the third
742 and fourth column of Table 2.

743 **Figure 5.** As in Fig. 4, but now separately for oceanic (panel (a)) and continental (panel (b))
744 conditions. Individual CVS class RFOs are also provided in the fifth and sixth column of Table 2.

745 **Figure 6.** Seasonal (month-by-month) variations of the zonal RFO of the four most dominant
746 CVS classes. (a) CVS="L"; (b) CVS="H"; (c) CVS="HL"; (d) CVS="HxMxL".

747 **Figure 7.** Graphical illustration of CRE strength for the various CVS classes. The graph shows the
748 area-weighted mean SW and LW CRE at both TOA and BOA, as well as the total (=SW+LW) CRE
749 in the atmosphere (middle of graph), a measure of heating or cooling induced by clouds in the
750 atmospheric column. CRE composite values come from collocated 2B-FLXHR-LIDAR data.

751 **Figure 8.** CVS RFOs within each of the MODIS CRs of O16. Conventions are the same as in Fig. 3.

752 To achieve spatiotemporal matching, only Aqua CR occurrences and daytime CVS data were
753 used.

754 **Figure 9.** As Fig. 8, but for the 1q and 3q subregimes (see text) of CR1(a), CR5(b), CR6(c), and
755 CR12(d).

756 **Figure A1.** Examples of CVS class assignment for the case of a single contiguous cloud layer.

757 **Figure A2.** Select examples of CVS class assignment for the case of two distinct (non-
758 contiguous) cloud layers.

759 **Figure A3.** Additional examples of CVS class assignment for the case two distinct (non-
760 contiguous) cloud layers.

761 **Figure A4.** Select examples of CVS class assignment for the case of three distinct (non-
762 contiguous) cloud layers.

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Figure 1.

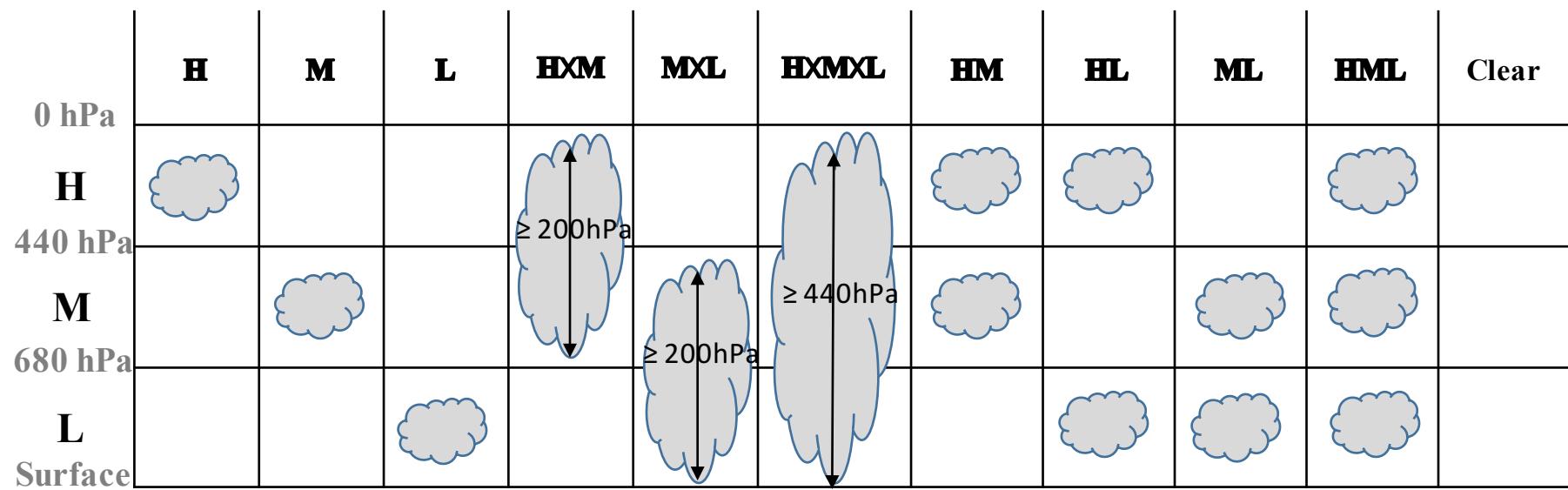


Figure 1

Figure 2.

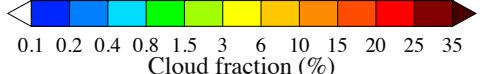
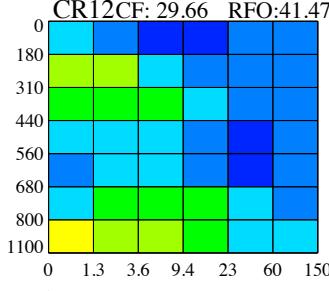
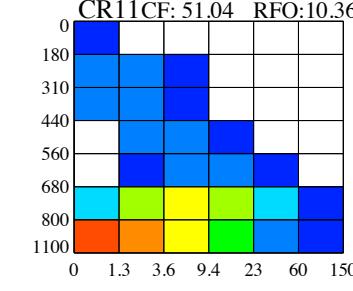
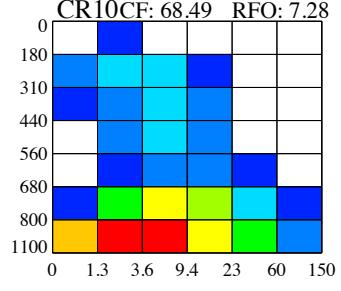
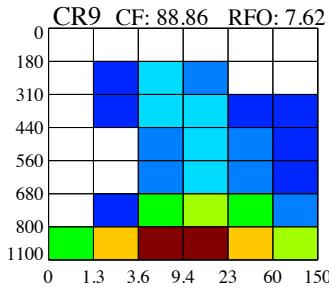
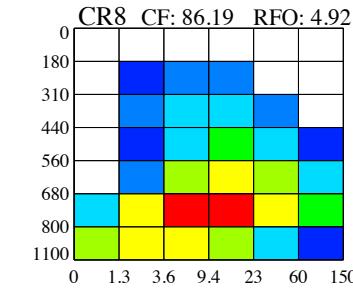
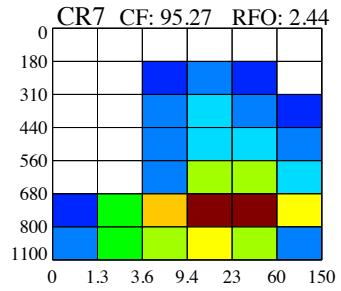
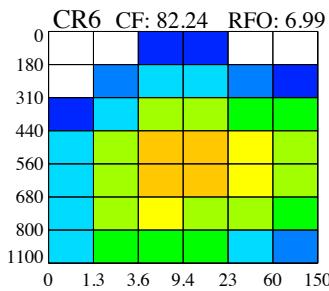
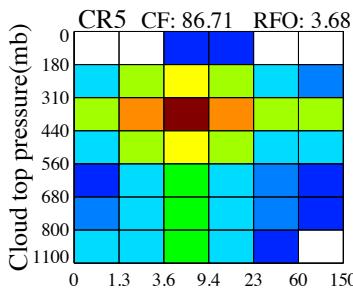
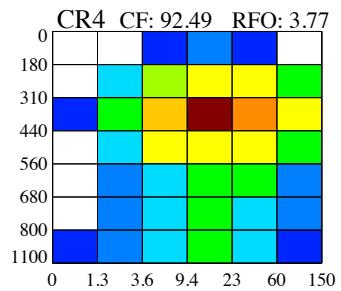
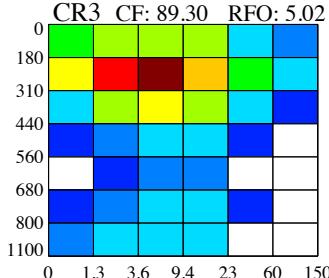
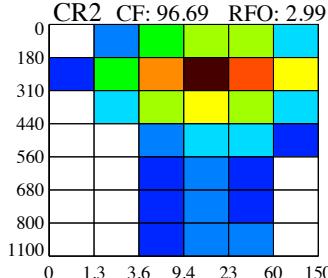
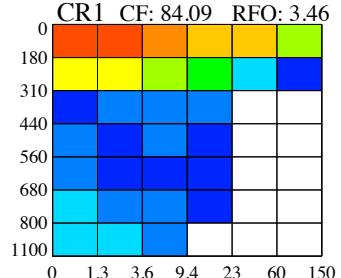


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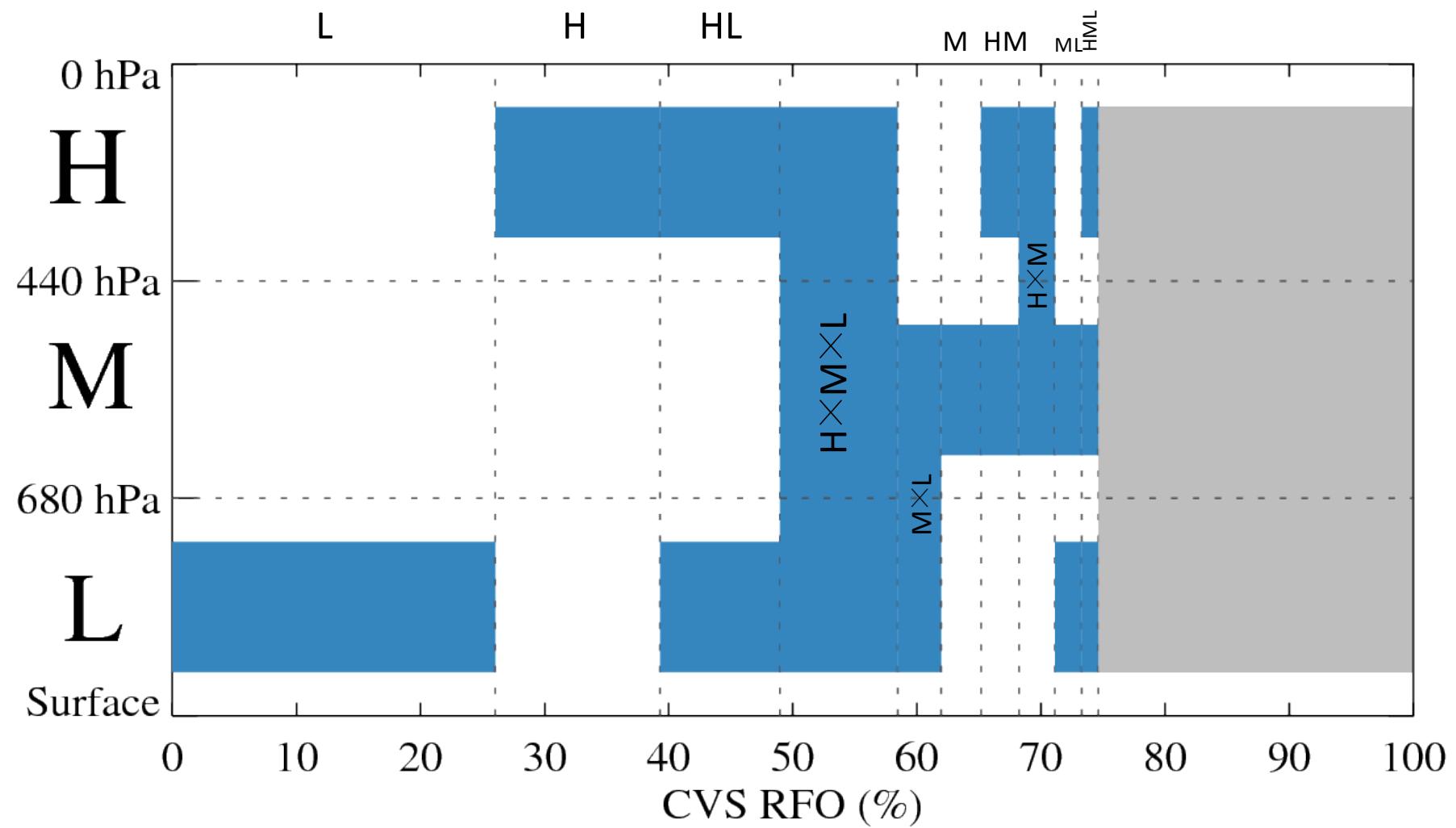


Figure 3

Figure 4.

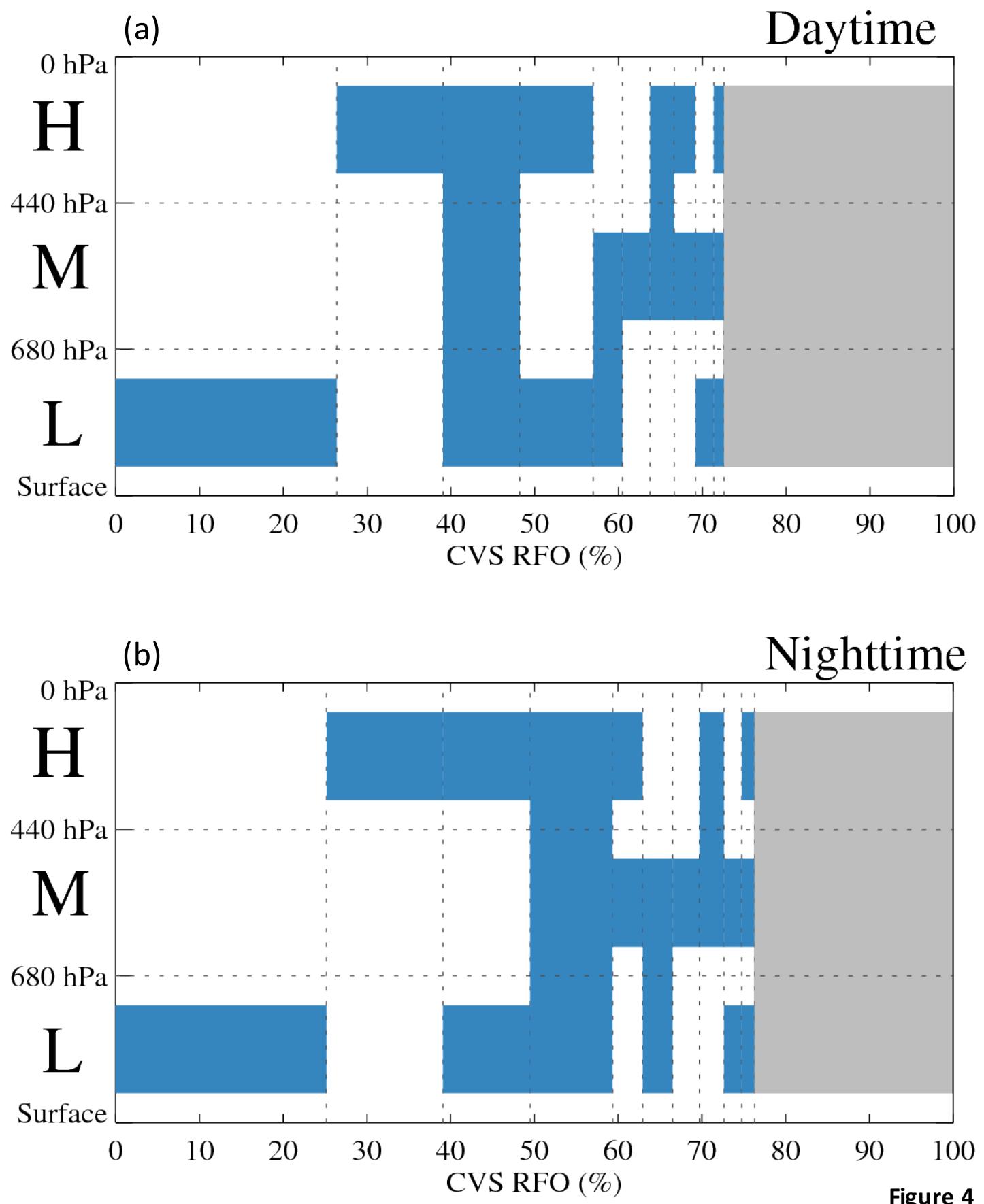
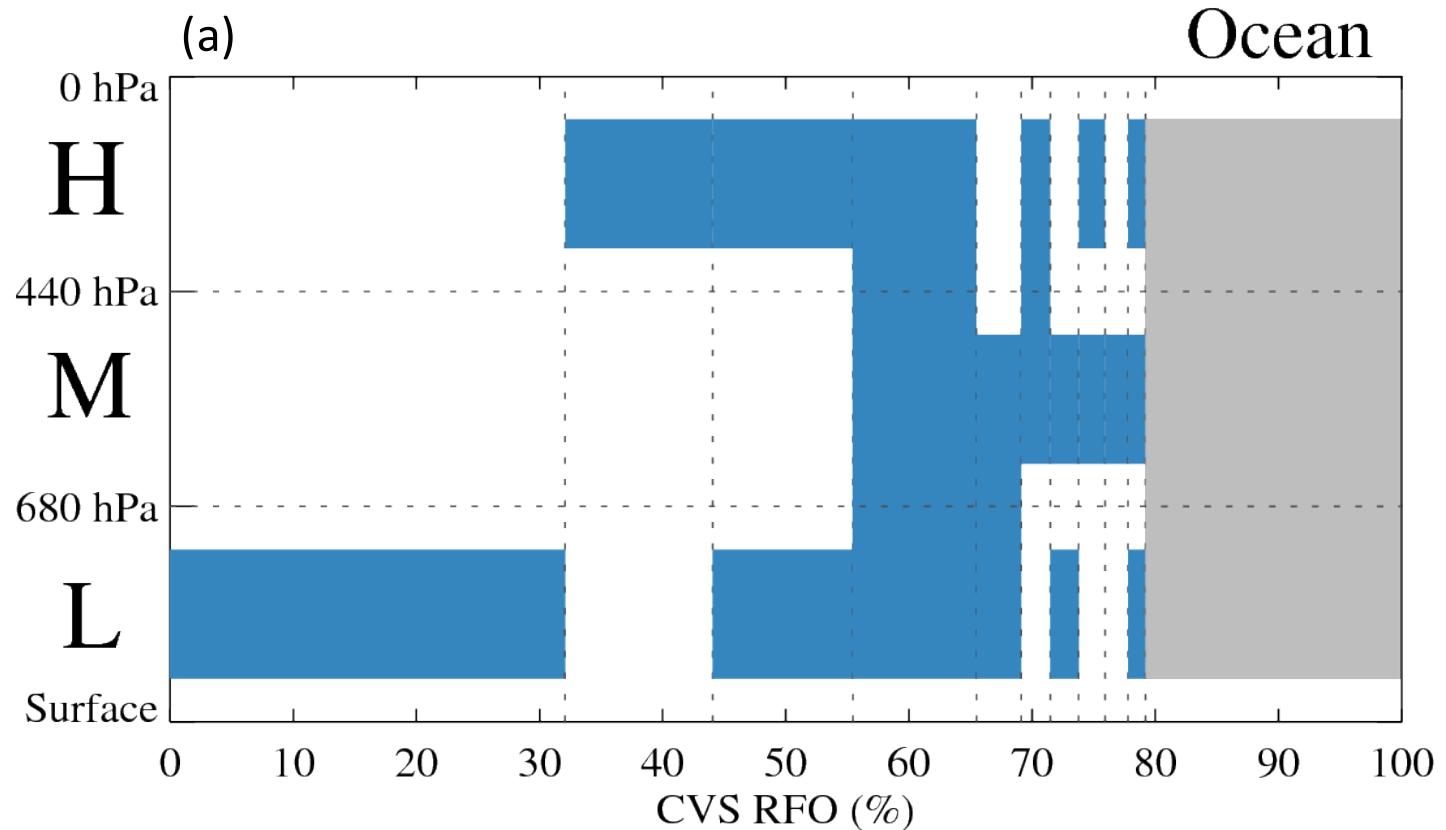


Figure 4

Figure 5.

Ocean



Land

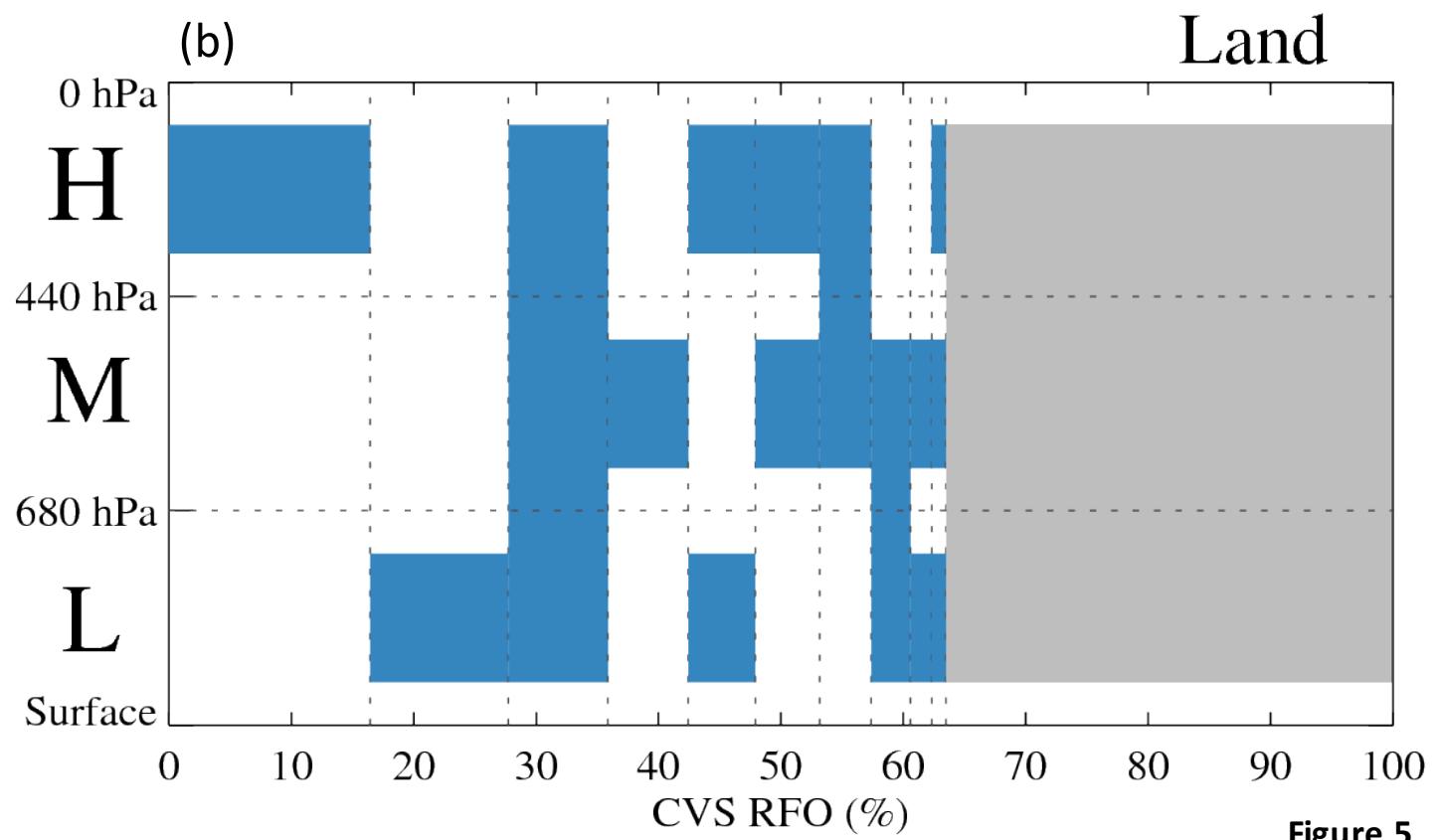


Figure 5

Figure 6.

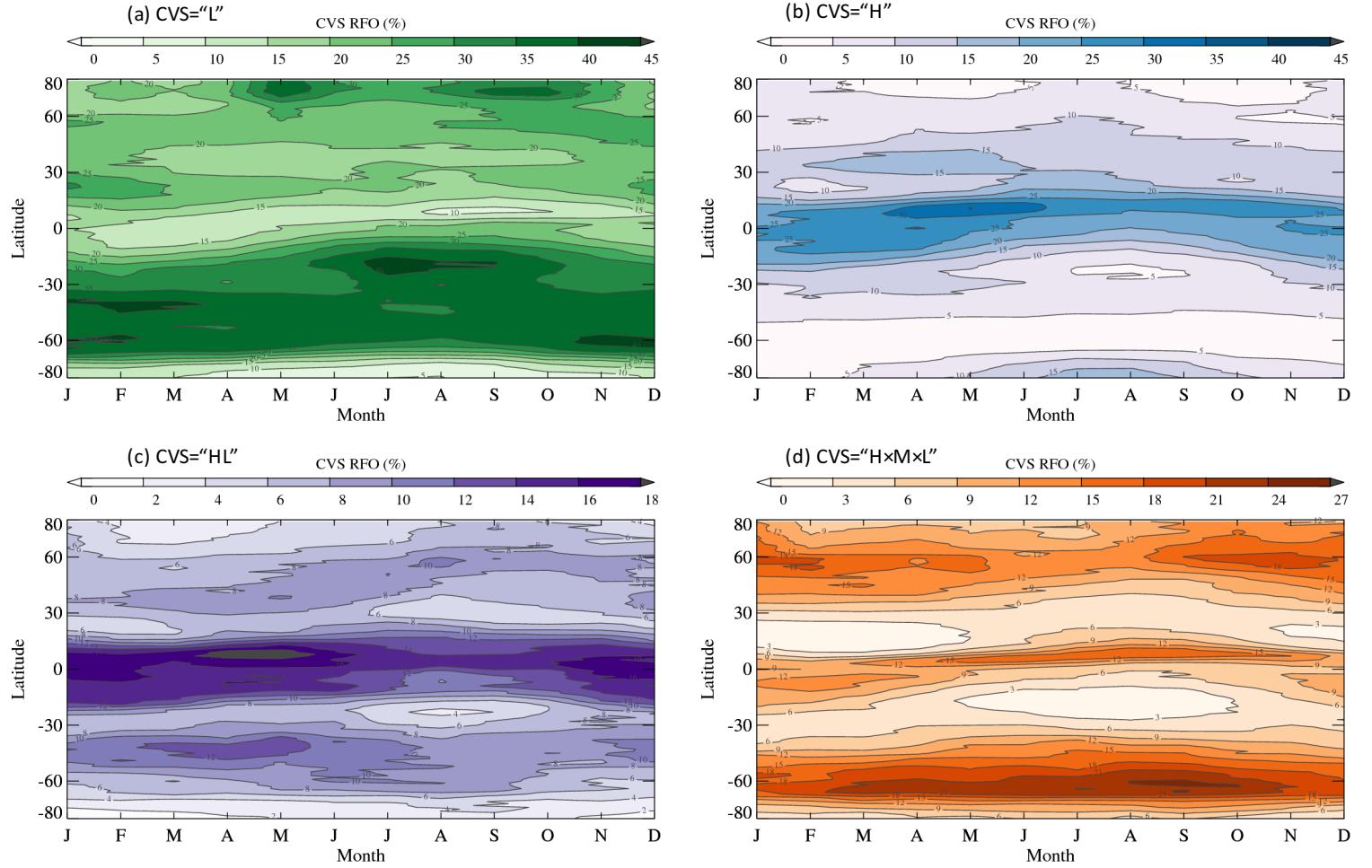
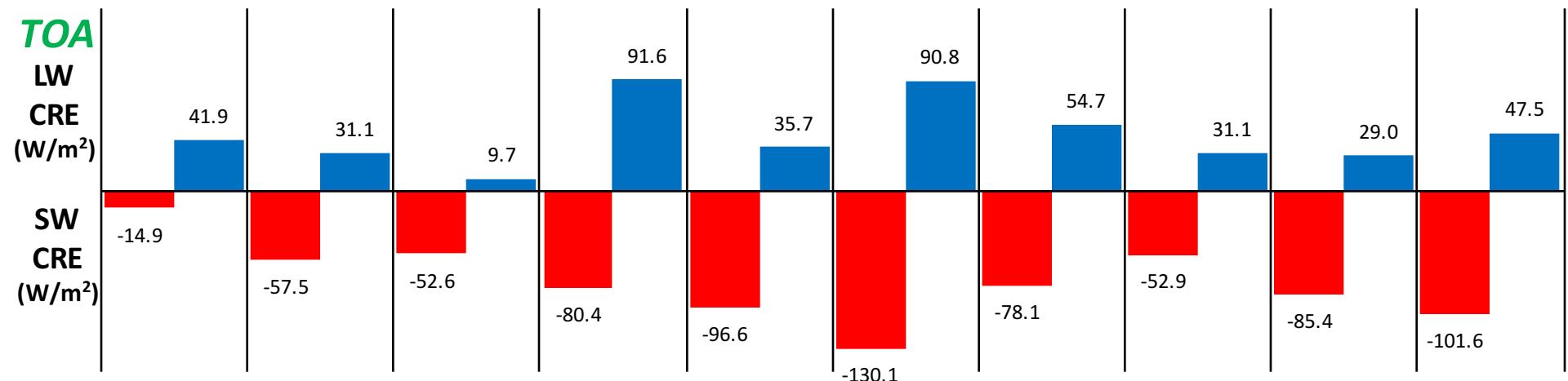


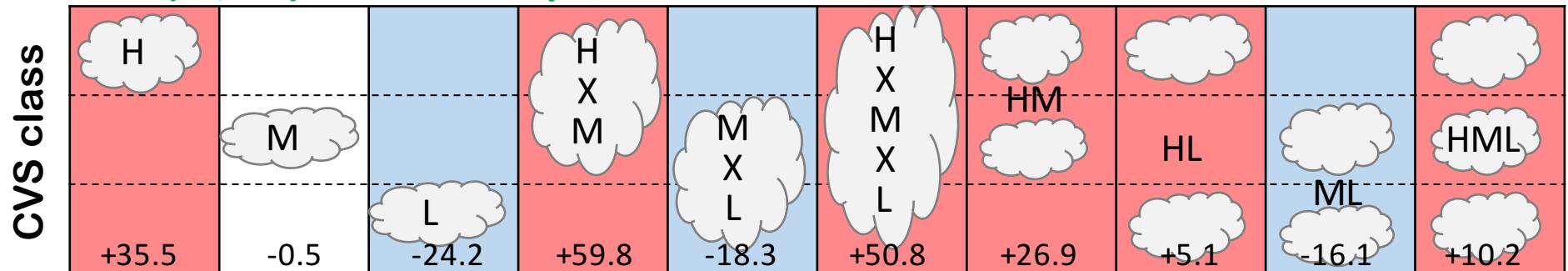
Figure 6

Figure 7.

Figure 7



Total CRE (W/m^2) in the atmosphere



BOA

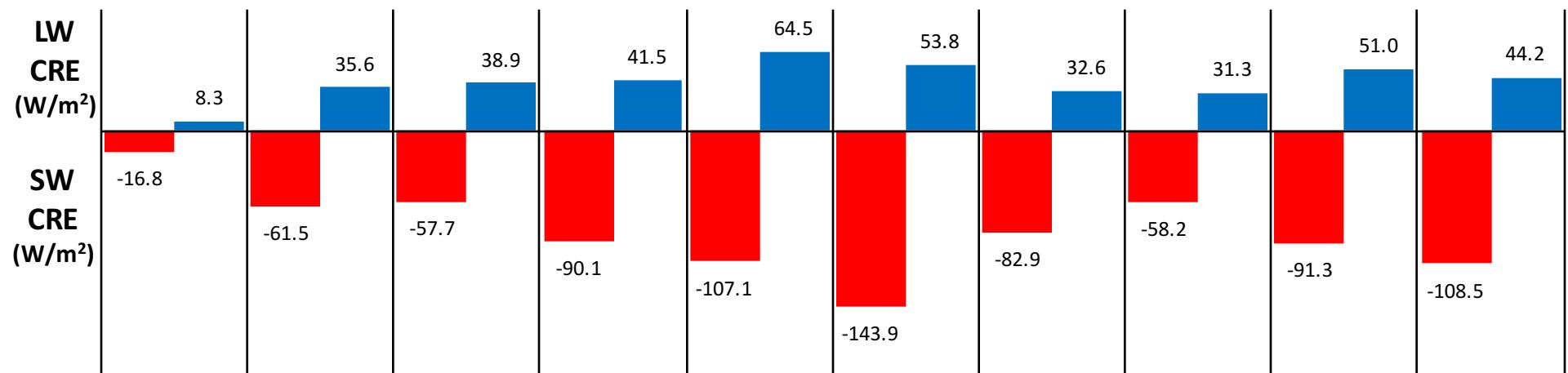


Figure 8.

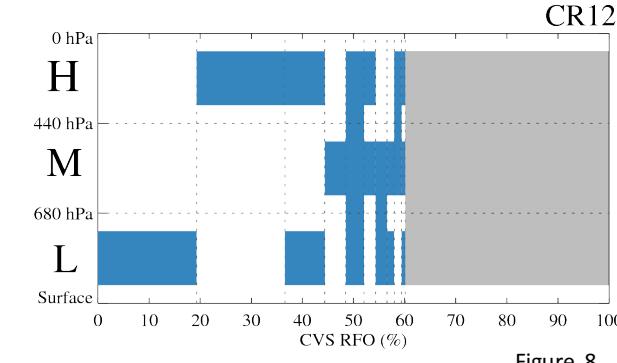
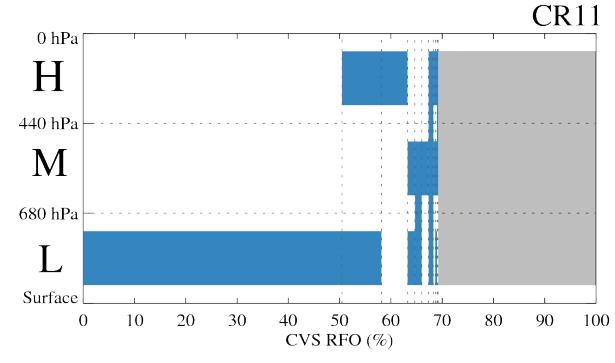
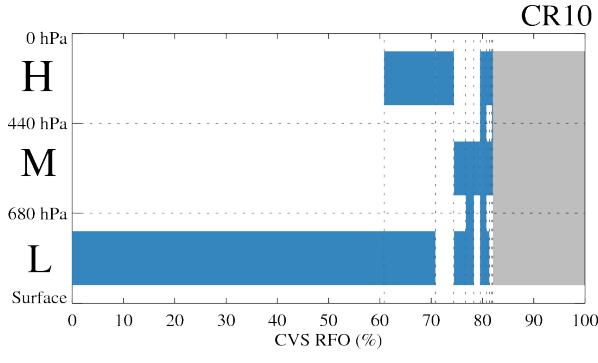
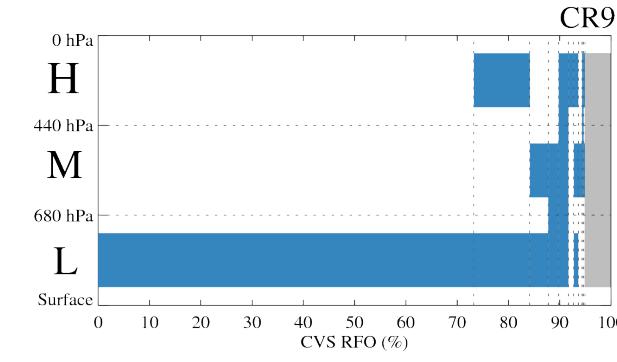
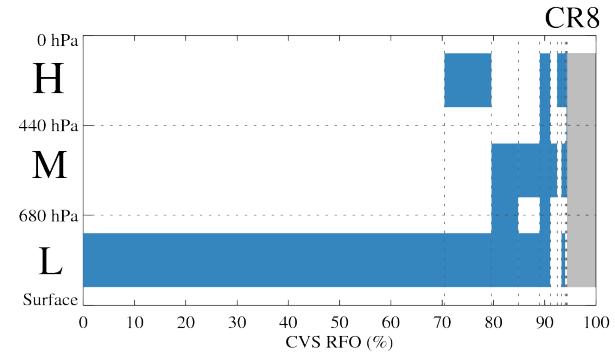
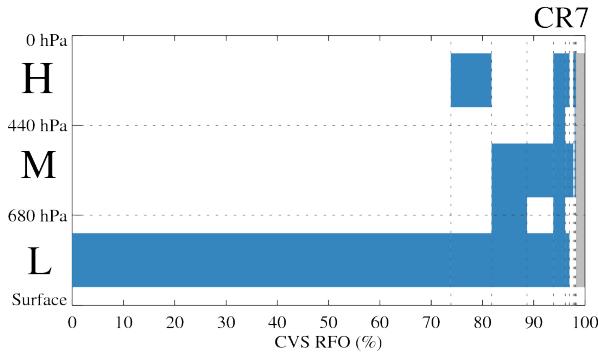
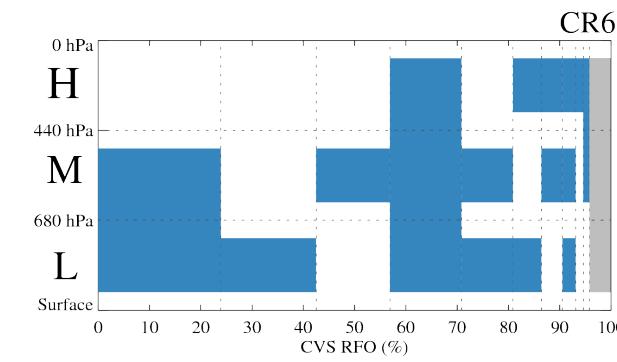
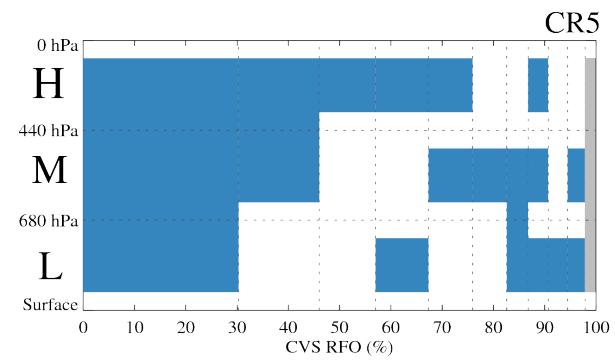
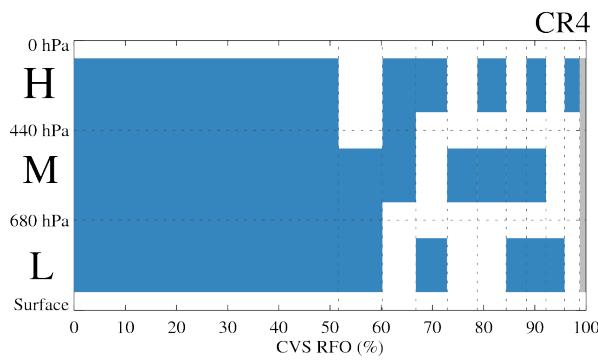
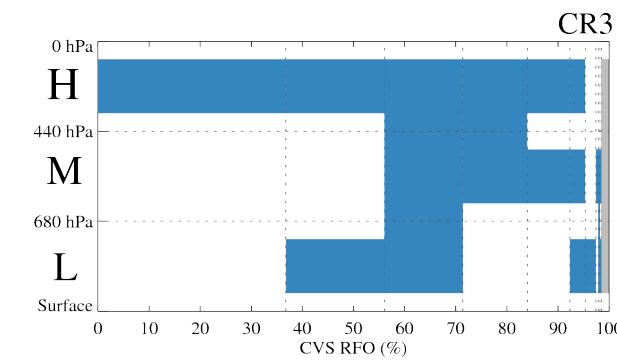
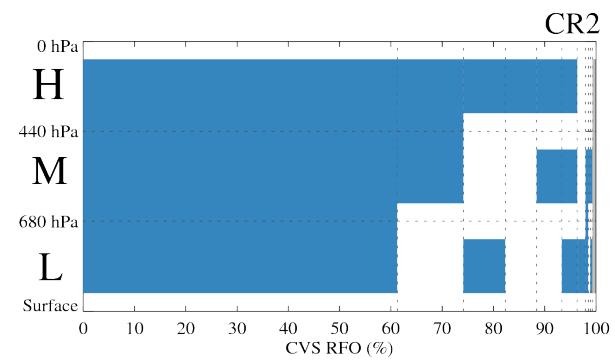
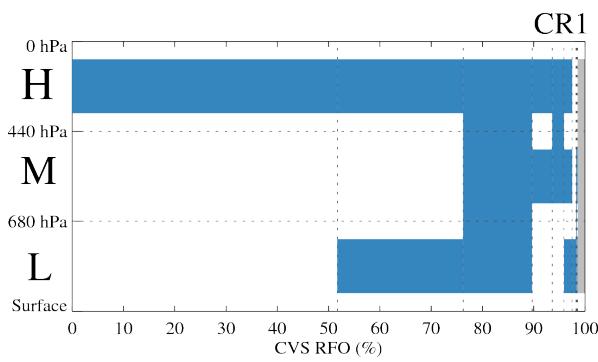


Figure 8

Figure 9.

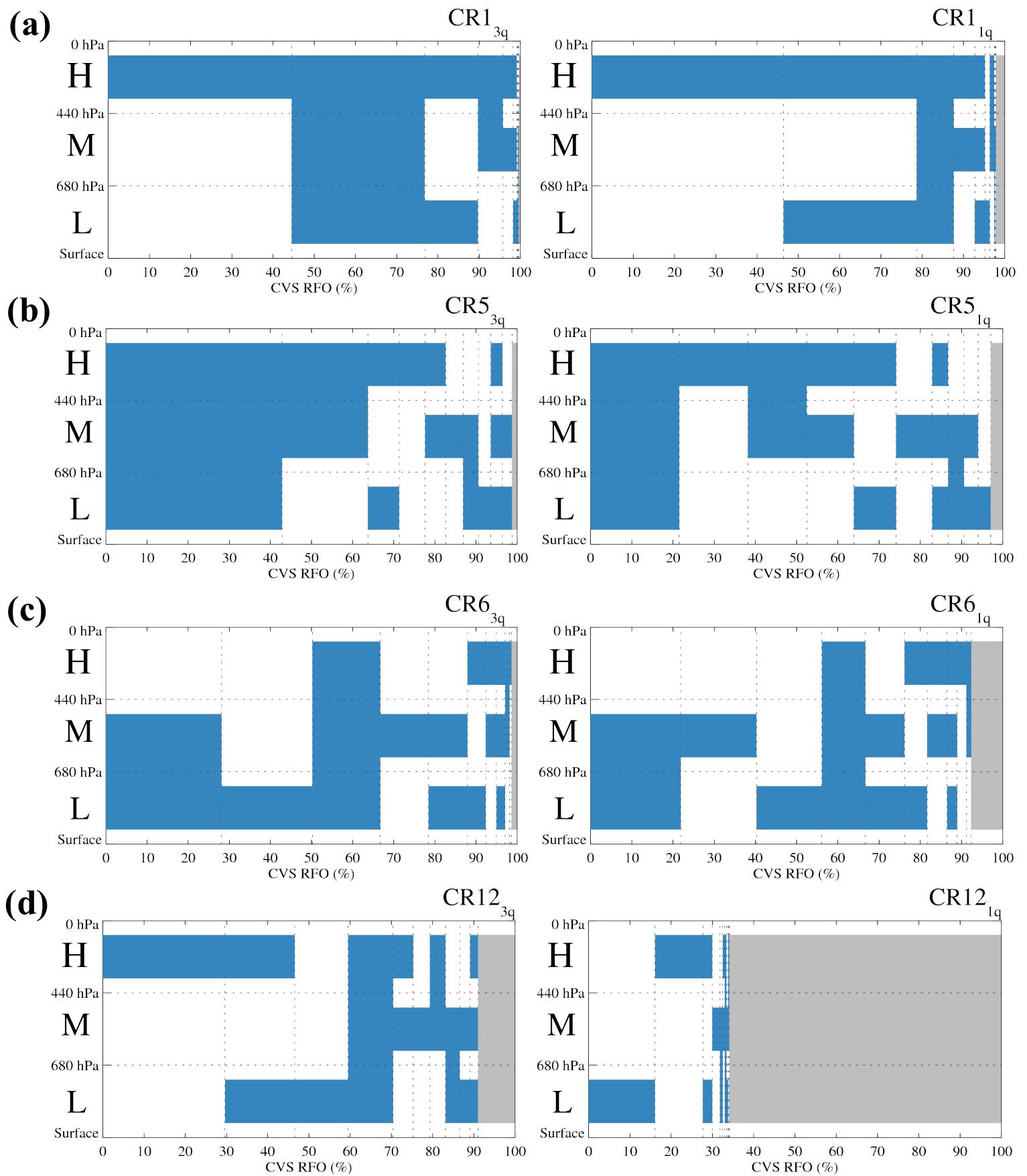


Figure 9

Appendix Figure 1.

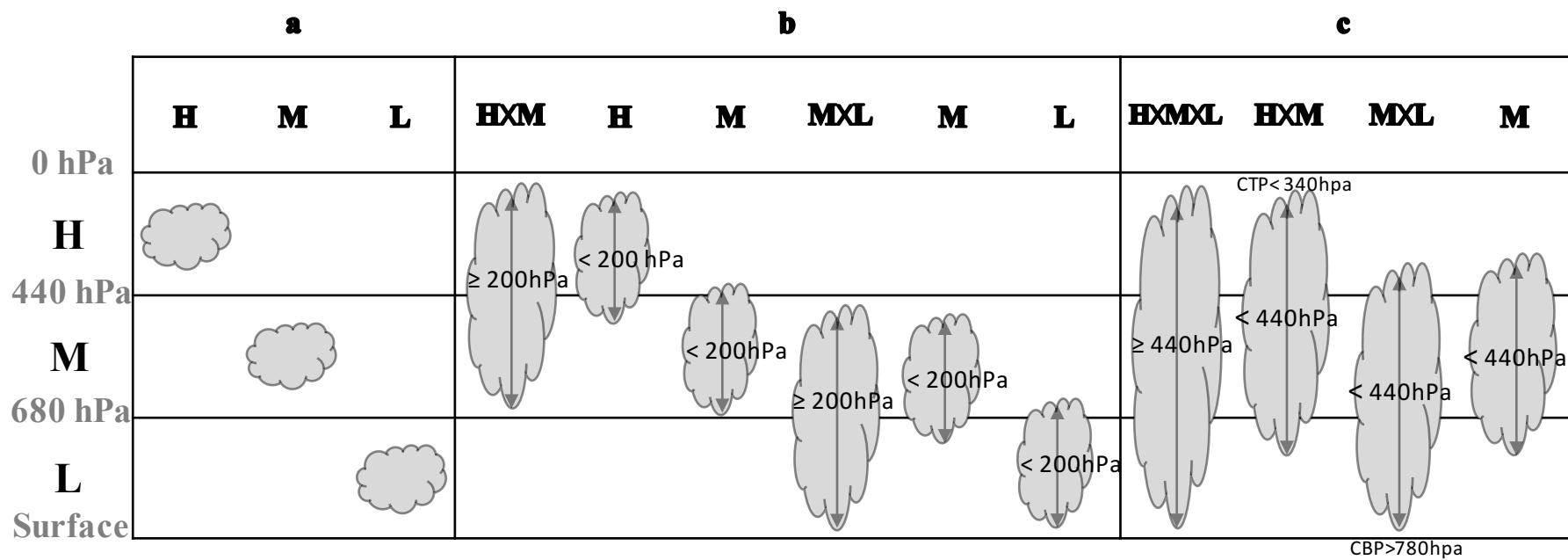


Figure A1

Appendix Figure 2.

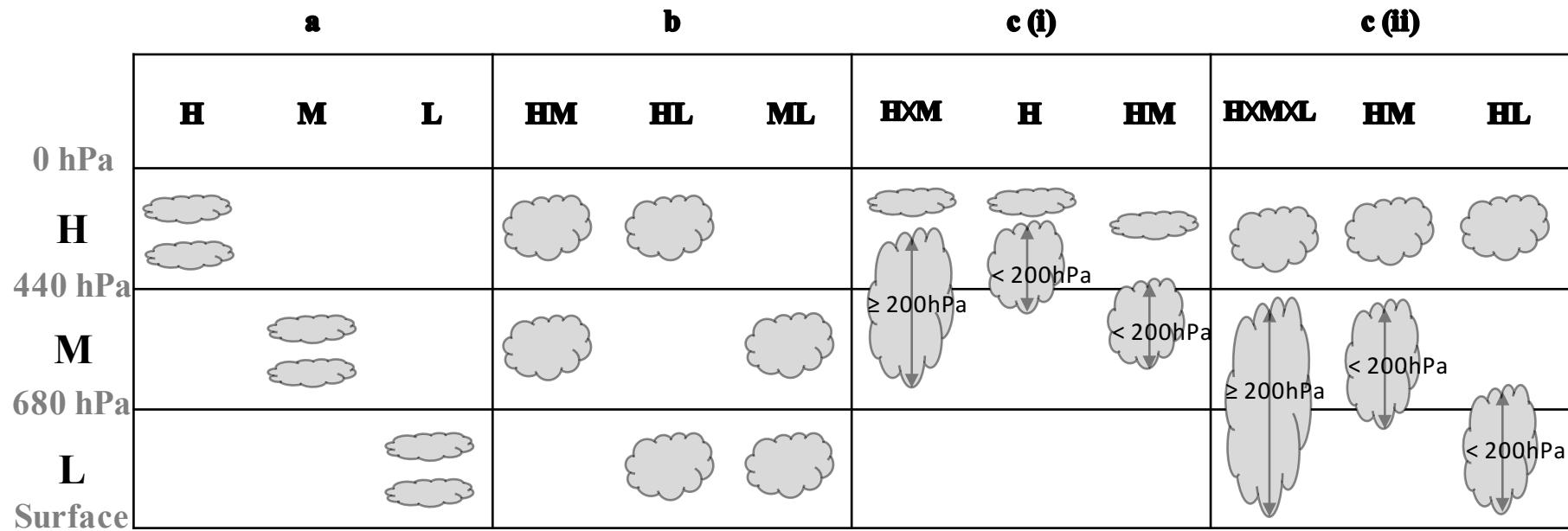


Figure A2

Appendix Figure 3.

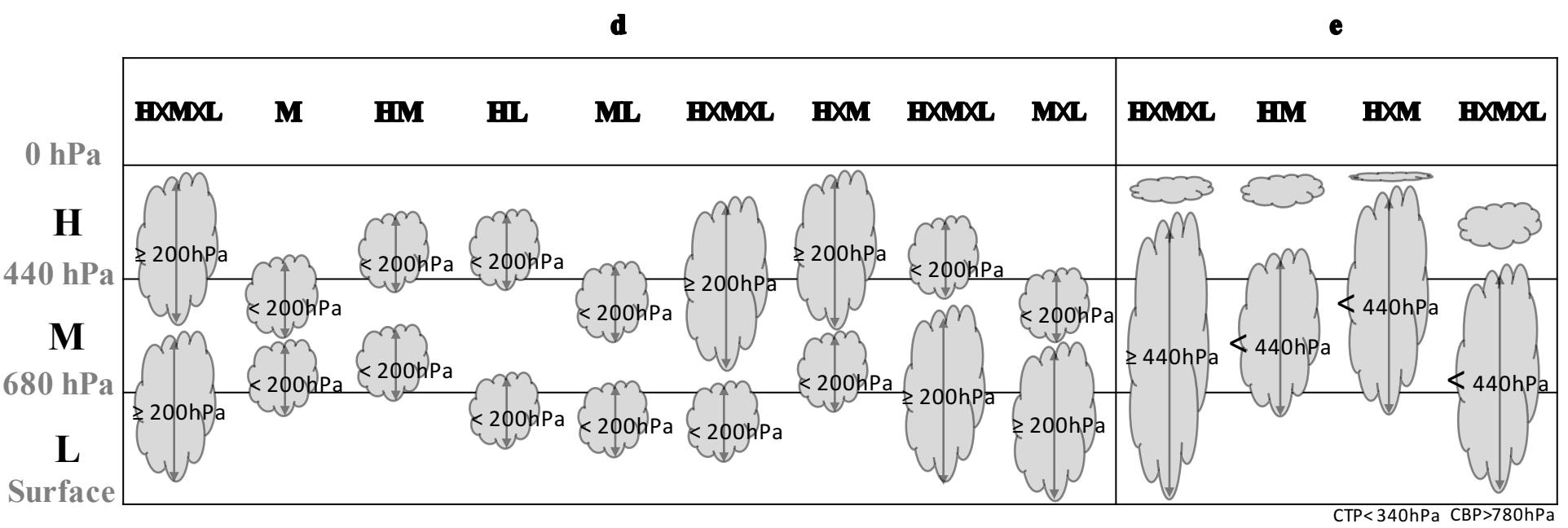


Figure A3

Appendix Figure 4.

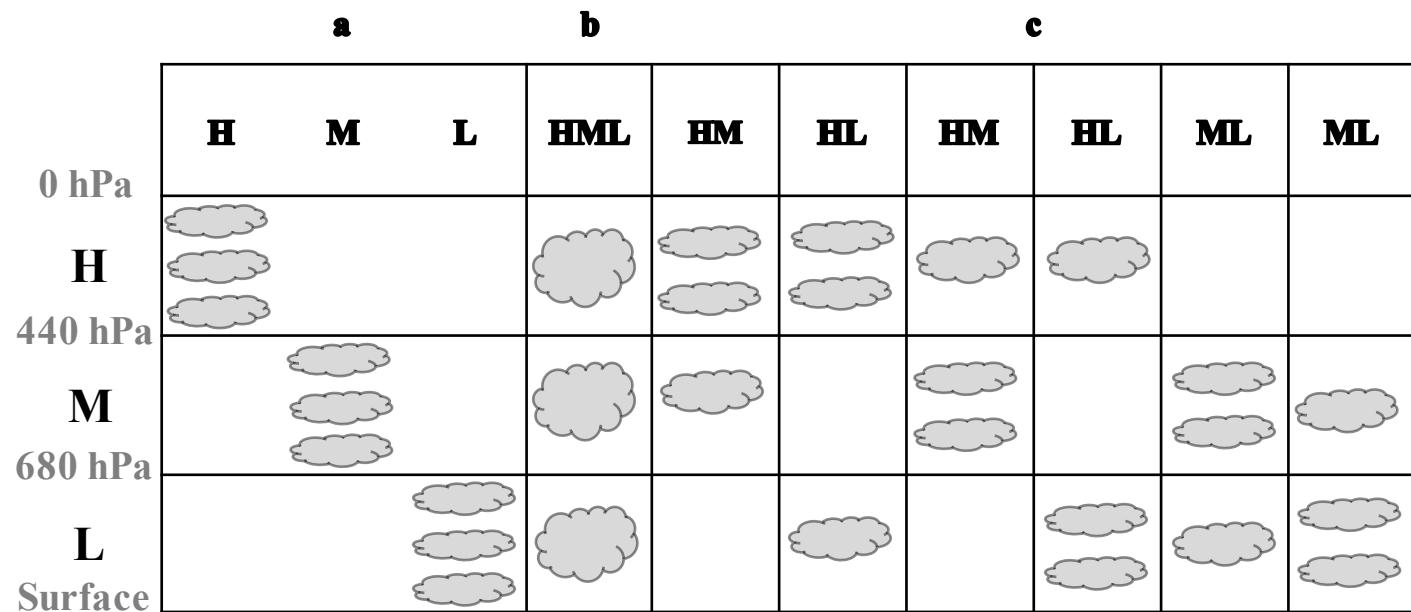


Figure A4